AUBURN UNIVERSITY

ECONOMIC ANALYSIS OF MATERIALS PROCESSING IN SPACE

Final Report
Contract NAS8-29881

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FOREWARD

This document is the final report for Contract NAS8-29881, "Economic Analysis of Materials Processing in Space." The work was performed by R. I. Vachon, R. C. Wilcox, A. W. Lacy, C. W. Hale, S. D. Beckett, and J. B. Canterberry of Auburn University, Schools of Engineering, Business, and Veterinary Medicine, for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center. The period of performance of this study was from March 1974 to June 1975.

ABSTRACT

Phenomena associated with reduced gravitational effects or "weightlessness" in outer space point to the possibility of the manufacture in space of improved materials, new materials, and innovative process techniques. Thus, an economic analysis using econometric and cost benefit analysis techniques was performed to determine the feasibility of space processing of certain products such as single crystals for electronic applications, high purity tungsten targets for medical x-ray tubes, turbine blades for jet aircraft engines, and electrophoresis for biological applications. Emphasis was directed to the analysis of turbine blades midway during the project by the direction of the sponsor. A detailed analysis of the cost of operating the space shuttle transportation system was necessary before each manufacturing process could be examined. All products or processes were analyzed as to the costs which will be incurred during space manufacture, the projected demands of such products during the 12 year planning period (1980-1991), and the benefits which can be derived from these improved products.

As indicated, space manufacturing of turbine blades was investigated in detail. This portion of the analysis included the types of furnace systems, molds, material storage systems, and materials handling equipment necessary to produce turbine blades in a fully automated system. The large number of blades which must be produced per year, the weight of these blades, the necessary equipment and the long process time requires a permanent space factory or station for the production of turbine blades.

Cost benefit analysis techniques applied to space processing of turbine blades indicate an adequate demand to justify production, substantial fuel savings of 6.522 billion gallons during the 12 year period (1981-1992), benefits over the 7.5 year life span of a blade of $991.50 per blade when used as replacements or over $21,000 per blade when used in new aircraft, and a total dollar savings to U.S. airlines in the period 1980-1992 of 6.618 billion. The best weight estimate for shuttle transportation of blade materials and other necessary equipment is 1.5 lb. (680.4 gm.) per blade with the residual factory cost (including development, launch and direct operation costs) of $369,482,727. All factors indicate a potential selling price of $991.50 per blade.

Space processing of high purity tungsten targets for medical x-ray tubes by containerless levitation melting would produce targets having higher milliampere ratings thus giving a smaller focal spot resulting in greater x-ray detail. Space processing to be successful is not dependent on reducing the Rhenium in the target but on the extension of target and tube life beyond the average two years life which now exists. Benefits derived from space processing were based on continued growth in demand for radiological health services and expected doubling of tube life. A doubling of the target life alone would produce a cost saving of over $14 million dollars for the 12 year planning period, assuming a 15 percent discount rate. However, transportation costs would appear to make space processing in this area uneconomical if only a doubling of life expectancy is assumed. Approximately, a three-fold increase in target life is required to cover space transportation cost.

Seven biological candidates for space processing using electrophoresis methods were examined. The most promising candidate was the separation of immunoglobulin (I_gG) into subclasses. Only 100 grams of I_gG separated into its four subcomponents could provide a serum that would be reproduced in animals. One shuttle flight would provide the U.S. needs for a year. This could be done on a regular shuttle flight and consequently provide high benefits for a relatively low cost.

In addition, an econometric model was developed to predict demand and supply figures for crystals over a time span roughly concurrent with that of NASA's Space Shuttle Program. The model was tested for crystal use in the electronics industry. However, work on the crystal study and the econometric analysis of crystals was terminated at the request of NASA project directors. A more in depth study has been funded with another contractor.

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1. INTRODUCTION

The stated objectives of this research project, as given in the original proposal were as follows:

a. Determine specific products or processes uniquely connected with space manufacturing.

b. Select a specific product or process from each of the following three areas: (1) semiconductors, (2) metals, and (3) biochemicals.

c. Analyze each of the products or processes selected in b above to determine the overall price/cost structure taking into consideration: total costs of materials, direct and indirect labor, other costs, depreciation/depletion/amortization, and income and benefits of all types.

The economic elements of the project were to involve three phases: (a) developing a generalized decision making format for analyzing space manufacturing, (b) a comparative cost study of selected processes in space vs. earth manufacturing, and (c) a supply and demand study of the economic relationships of one of the manufacturing processes.

The project was organized in a manner to provide substantial interplay between Marshall Space Flight Center and the project and task team leaders. Feedback from Marshall allowed the project to proceed as evolutionary research rather than precisely as the project proposal outlines. The basic objectives set forth have been met substantially, however.

1.0.1 Concepts of Space Processing

Three concepts of space processing were explored to some degree. The first involved the type of operation in which a factory was itself transported up in the shuttle, operations carried out, and then returned in the shuttle. This process poses high transportation costs and was considered non-economical for most manufacturing type operations. A possible exception would lie in biomedical area, where some production could take place on regularly scheduled shuttle flights.

The second concept was that of an automated unmanned space factory that would be launched separately, if necessary, from the shuttle. The factory would remain in orbit and be serviced by the shuttle. This mode of production is analyzed in Section 1.4. Finally, some consideration was made of utilizing a permanently launched manned space factory.

1.1 Selection of Product Lines

The products that were chosen for analysis of space processing feasibility were:

a. Turbine blades

b. Tungsten targets for x-ray machines

c. I_gG subclass separation by electrophoresis

d. High-price exotic crystals

Individual reports on each of these products can be found in Chapters 3.0, 5.0, 6.0, and 7.0, respectively. In addition, an analysis devoted to the space processing facility for turbine blades is given in Chapter 4.

The selection of the product lines was delineated somewhat by selecting (a) only product lines that potentially would provide substantial technical improvement over earth processing, or (b) product lines that have not yet been producible in earth gravity. The decision to do this was based on the assumption that the added cost of space transportation would negate almost all earth vs. space manufacturing considerations. Conceivably, some products manufactured in space could increase production reliability to the extent that transport costs would be offset. The only product line of this type identified was crystals, which also bore heavy quality improvement potential. Interest was consequently placed on improved quality and performance aspects derived from space processing. Throughout the analysis, the assumption was made that all costs, including transportation costs must be recovered for the produce to be viable.

1.2 Shuttle Costs

Shuttle Costs were based on the volume of traffic anticipated by the October 1973 Shuttle Traffic Model. A 32,000 pound cargo capacity was assumed. Average cost curves were calculated on the bases of differing levels of activity per year. The levels chosen were 12, 20, 30, 40, 56, 60, 70, and 82 flights per year.

The costs were calculated using parametric estimation techniques but do not reflect detailed engineering estimates which would be used in budget requests. Some estimates regarding total costs were obtained fr Mr. H.C. Mandell and Mr. John Wise of the Space Shuttle Resource Management Office, NASA, Houston. Learning curves of 85 percent and 95 perce t ere used to compute economies of scale.

In addition, each cost computed was discounted to obtain present values for 0, 5, 10, and 15 percent discount rates. The purpose of discounting is to account for alternative or opportunity costs. The rational is presented in Appendix 2-1.

1.3 Turbine Blades

The greatest portion of research effort on this project has been devoted to the analysis of turbine blades as a potential candidate for space processing. In addition to a cost-benefit analysis, a section devoted to the operation of a space factory is presented.

The feasibility of turbine blades for space processing was analyzed by comparing the potential benefits with the potential costs. The potential benefits were estimated by assuming a higher level of performance from a technologically superior blade. Savings were calculated for the U.S. commercial airlines, using projections of future flight levels. Savings aspects considered were fuel savings, capital savings, and operational savings. These savings are large and provide considerable value to offset the costs of the space factory itself. Other costs are estimated and a residual allowable cost for the space factory is cálculated. The results indicate that turbine blades are a strong candidate for space processing.

1.4 Turbine Blade Processing

Space processing of directionally solidified eutectic-alloy type turbine blades is envisioned as a simple remelt operation in which pre-cast blades are remelted in a pre-formed mold. Such a process requires a permanent space factory because of the weight of the large number of blades (172,800) which must be produced annually, the weight of the processing facilities, and the long process times involved. Three different furnace process systems based on induction melting, continuous resistance furnaces, and batch resistance furnaces were evaluated. The development of each system involved the necessary number of furnaces, the number of blades required per mold, the allowable mold density, the general furnace design, and the materials storage facility. Also, the general type of materials handling equipment, the necessary volume required to house each total facility, and the general power requirements are discussed.

1.5 Tungsten Targets for X-Ray Tubes

The approach taken to the analysis of tungsten targets for X-Rays was similar to that of the turbine blades, considering the costs and benefits. The benefits of space manufacturing, however, appear limited to increasing the useful life of the target. Although substantial benefits may be anticipated from this source, the transportation costs would appear to make space processing in this area uneconomic if only a doubling of life expectancy is assumed.

1.6 Electrophoresis

Seven candidates for space processing using electrophoresis methods were examined. These were: a) Pure samples of four subclasses of I_gG b) Pure cultures of Beta cells, c) Pure cultures of stem cells without compliment fixing cells, d) Pure cultures of tumor cells, e) Urokinase producing cell, f) Pure samples of antihemophilic factors, g) Pure cultures of B & T cells. Selected as a promising candidate for space processing was the immunoglobulin (I_gG) subclasses. Since 100 grams of I_gG separated into its 4 subcomponents could provide a serum that would be reproduced in animals; only one flight is needed to provide the U.S.

needs for a year. This could be done on a regular shuttle flight and consequently would provide high benefits for a relatively low cost.

1.7 Crystal Study and Econometric Model

Work on the crystal study and the econometric model was terminated at the request of the NASA project directors. To deal with this problem, NASA has funded another agency to make a more in depth study. The analysis presented represents work completed and the plan for completing the work. Data gathered is presented.

The crystal study presented problems for econometric analysis due to an almost total lack of time series data. Consequently, many proxies were used to develop a testable model. The model was tested using the electronics industry as a sample while efforts to gather crystal data were underway. These results are presented. Crystal data proved to be too short term for the model in general. The model could have been used in a crystal using few product lines, however.

1.8 Meeting of Objectives

The objectives of this research were set forth in Section 1.0 above. In line with these objectives the report:

a. Specifies products that would benefit technologically from space processing.

b. Selects products from each of the three areas: a) semiconductors - crystals, b) metals - turbine blades and tungsten targets, c) biochemicals - I_gG subcomponents.

c. Analyzes each of the products, with the exception of crystals, for costs and benefits. The crystal study was terminated before cost - benefit analysis began. This was done in a meeting with NASA officials on December 13, at MSFC. At this point work on the econometric model for crystals and the crystal study was shifted to concentrate on the turbine blade and turbine blade processing facility.

A judgement was made as to the potential feasibility of the products for space processing. The turbine blade and I_gG products were described as promising candidates. The outlook of tungsten targets for X-rays was not. No judgement was made on crystal feasibility.

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2. SPACE SHUTTLE

2.1 Introduction

In order to determine the feasibility of selected material processes for adaptability to space processing, it was necessary to estimate the costs of operating the space shuttle transportation system (SSTS). Three types of cost estimates must be made. The first cost allocation involves the transportation costs associated with space materials processing. The second cost allocation involves the specific processing costs associated with the space materials processing facility (SMPF). The third cost allocation deals with the integration of shuttle payloads on the ground.

This section is concerned only with the costs of space transportation. The following assumptions were used in developing the cost estimates presented in this section:

a) The October 1973 Shuttle Traffic Model was used as a basis for calculating all costs.

b) All Shuttle flights are evenly distributed over the 1979-1990 planning period.

c) A 32,000 lb. cargo payload is the maximum capacity of the Orbitor.

d) The Orbitor will use a 200 N.M. orbit at an inclination of 28.5°. All Shuttle flights will originate at the Florida launch site.

e) The Cost calculations are based on 986 Shuttle flights.

The following conventions and procedures were followed:

a) All values are represented in 1972 dollars except where otherwise stated.

b) All future transportation costs are discounted at 0, 5, 10, and 15 percent discount rates.

c) All joint costs are allocated to the user on the basis of a charge per pound of Orbitor cargo capacity. This is paramount to saying that all space transportation costs are presented on a payload cargo pound basis.

d) The transportation charges are presented three ways:

1) Minimum cost analysis: includes only the operating and maintenance costs of the shuttle transportation system.

2) Minimum total operating and capital amortization costs: all costs included in the minimum cost analysis and amortization charges for non-DOD Orbitor investment expenditures and related ground facilities.

3) Full costs of amortizing operating, investment, and development expenditures: includes(1) and (2) and the development costs of the Orbitor.

For purposes of calculating transportation costs of space processing activities, the figure of $326 per pound was chosen. This is taken from Table 2-1 assuming the scheduled 12 year total flights to be 445 or 37 per year. This figure is for a zero discount rate and is believed to be a very conservative figure. Should space processing become a viable space activity, the increase in total flights could result in learning economies that potentially would decrease this figure substantially. For example, the costs per pound for a high level of activity, 82 flights per year for 12 years, with a zero discount rate would place the per pound cost at $260 a year. This figure represents a substantial reduction in total costs for space processing.

TABLE 2-1: SPACE SHUTTLE COST ESTIMATES FOR SELECTED LEVELS OF FLIGHT ACTIVITY AND A ZERO DISCOUNT RATE FOR A 12 YEAR PLANNING PERIOD[4]

ANNUAL FLIGHTS	12 YEAR TOTAL FLIGHTS[1]	AVERAGE COST PER FLIGHT[2] ($1,000,000)	TOTAL COST ($1,000,000)	MARGINAL COST PER FLIGHT ($1,000,000)	TOTAL CARGO (1000 lbs.)[3]	COSTS PER POUND ($)
12	144	16.712	2406.528	7.8702	4608	522
20	240	13.113	3147.120	7.8510	7680	409
30	360	11.107	3998.520	7.8270	11520	347
37	445	10.450	4639.800	7.8100	14208	326
40	480	10.153	4873.440	7.8030	15360	317
56	672	9.228	6201.216	7.7646	21504	288
60	720	9.032	6503.040	7.7550	23040	282
70	840	8.711	7317.240	7.7310	26880	272
82	984	8.350	8216.400	7.0220	31488	260

NOTES:

(1) 12 year planning period
(2) 200 N.M. orbit, 28.5° inclination
(3) 32,000 lb. cargo load
(4) 1972 Dollars

SOURCE:

Estimates shown in column 3 were obtained from Mr. H.C. Mandell and Mr. John Wise of the Space Shuttle Resource Management Office, NASA, Houston.

2.2 Description of the Orbitor

The Space Shuttle cost estimates contained in this analysis are based on the approximately 986 Shuttle flights allocated among different orbits by the October 1973 Shuttle Traffic Model[1].* However, direct delivery of the maximum Shuttle cargo payload is limited to relatively low orbits. The delivery of the payloads to higher orbits requires an additional propulsion stage and propellent load that must be carried along with the cargo payload.

The Shuttle has a cargo capacity of 65,000 pounds that can be launched in a due east orbit from Cape Kennedy into a 220 nautical mile orbit. The alternative launch site at Vandenberg Air Force Base allows for polar missions to be flown with a launch capacity of 40,000 pounds. In cases of emergency the Shuttle can land with a full cargo payload, however, the Shuttle is designed to return 32,000 pounds of cargo payload to earth.

The low orbital missions, including Space Material Processing activities, will be flown from Cape Kennedy; polar missions will be flown from Vandenberg Air Force Base. The high orbit flights will require the use of the space tug--the tug is used to move the basic payload into orbit beyond 220 nautical miles; at present it appears that approximately 50 percent of the Shuttle flights will use the tug [2].

The October 1973 Shuttle Traffic Model indicates that many flights will have a higher orbit than 220 nautical miles so that the 32,000 pounds of cargo capacity would not be available for the payload only but would have to be used partially for additional fuel and equipment required for the higher orbits. This would increase the cost of placing a pound of cargo into a zero gravity environment.

The implication of this payload limitation can be grasped more clearly if the weight characteristics of several Space Lab configurations are given

* Numbers refer to citations at the end of the chapter.

in some detail. The Spacelab configurations characteristic of Space Shuttle Transportation System (SSTS) flights include a pallet only, a pressurized module only, and a pressurized module with a pallet [3].

(a) pallet only example:

Orbit Required:
28.5° Inclination, 100 nm (185 km) Circular

Typical On-Orbit Performance Available:
65,000 lb. (29,484 kg)

Design Constraint: 25,000 lb. (11,340 kg) Landing Wt.

Spacelab Weight:
Five 9.8 ft. (3.0 m) Pallet Segments
7,602 lb. (3,450 kg)

*Payload Available to User: (including Spacelab chargeable items)
25,000 - 7,602 = 17,398 lb. (7,890 kg)

(b) pressurized module only:

Orbit Required:
45° Inclination, 470 nm (870 km) Circular

Typical On-Orbit Performance Available:
30,000 lb. (13,600 kg)

Design Constraint: 25,000 lb. (11,340 kg) Landing Wt.

Spacelab Weight:
2,127 Tunnel
10,759 Support Section
2,249 Experiment Section
390 Aft Bulkhead
15,525 lb. (7,042 kg)

*Payload Available to User: (including Spacelab chargeable items)
25,000 - 15,525 = 9,475 lb. (4,298 kg)

(c) pressurized module with pallet

Orbit Required:
56° Inclination, 100 nm (185 km) Circular

Typical On-Orbit Performance Available:
40,000 lb. (18,144 kg)

Design Constraint: 25,000 lb. (11,340 kg) Landing Wt.

Spacelab Weight:

2,032	Tunnel
10,759	Support Section
390	Aft Bulkhead
3,903	Three Standard Pallet Segments
17,084 lb.	(7,749 kg)

*Payload Available to User: (including Spacelab Chargeable items)

25,000 - 17,084 = 7,916 lb. (3,591 kg)

In the examples given above, the design constraint associated with landing the cargo payload is 25,000 lbs. The difference between the design constraint weight of 25,000 lbs. and the total landing cargo weight of 32,000 lbs. constitutes a program reserve, which is primarily intended to provide for additional cargo payload. For this reason the cargo payload is treated as 32,000 lbs. in this study [4].

It should be noted that the Spacelab configurations represented in the preceding three examples were developed for experimental work and do not represent the kind of Space Material Processing Facility (SMPF) that will probably be in use during the commercial phase of space processing activities. However, these configurations are suggestive of the cargo capacities of the Shuttle where sortie flights are to be launched. Sortie flights may be used in commercial applications of electrophoresis in space.

The most densely traveled orbit according to the October 1973 manifest will be 28.5° inclination at 220 nautical miles. This orbit would allow for a cargo payload of approximately 32,000 lbs. This of course assumes that the entire Orbiter capacity is used to transport cargo payloads.

The key element in the SSTS program is the Shuttle. The Space Shuttle consists of a reusable orbiter vehicle, twin rocket boosters that are reusable, and an expendable external propellant tank. The reusable orbiter and twin rocket boosters allows a cost savings of approximately $14.1 million for the 12 year planning period over the material requirements for expendable rockets.

The orbiter will carry a basic flight crew of 3 persons and can carry in addition from 1 to 4 technicians and scientists. The orbiter has a cargo bay 18 meters (60 feet) long and has a diameter of 4.5 meters (15 feet). The cargo bay can accommodate a cargo load of 14,500 kilograms (32,000 lbs.) for a 220 nautical mile due east orbit.

The overall funding requirements for the Shuttle elements of the NASA Shuttle-Spacelab program amounts to approximately $7.417 billion (1971 dollars). This reflects a development cost of $5.394 billion and additional procurements of hardware and facilities amounting to $1.345 billion. The hardware inventory for the Shuttle part of the program includes: [5]

(a) 3 production orbiters
(b) 2 refurbished orbiters
(c) 4 production boosters
(d) 2 development boosters (if not expended during development).

The turn around cycle for the Shuttle is estimated to require approximately 160 hours from landing to launch. Deactivation, cargo removal, etc. will require approximately 10 hours; maintenance of the Shuttle 85 hours, Shuttle assembly 48 hours, and pre-launch systems checks, propellent loading, etc. will require about 17 hours [6].This scheduling and hardware inventory would allow for as many as two Shuttle launches per week.

2.3 Shuttle Operational Costs

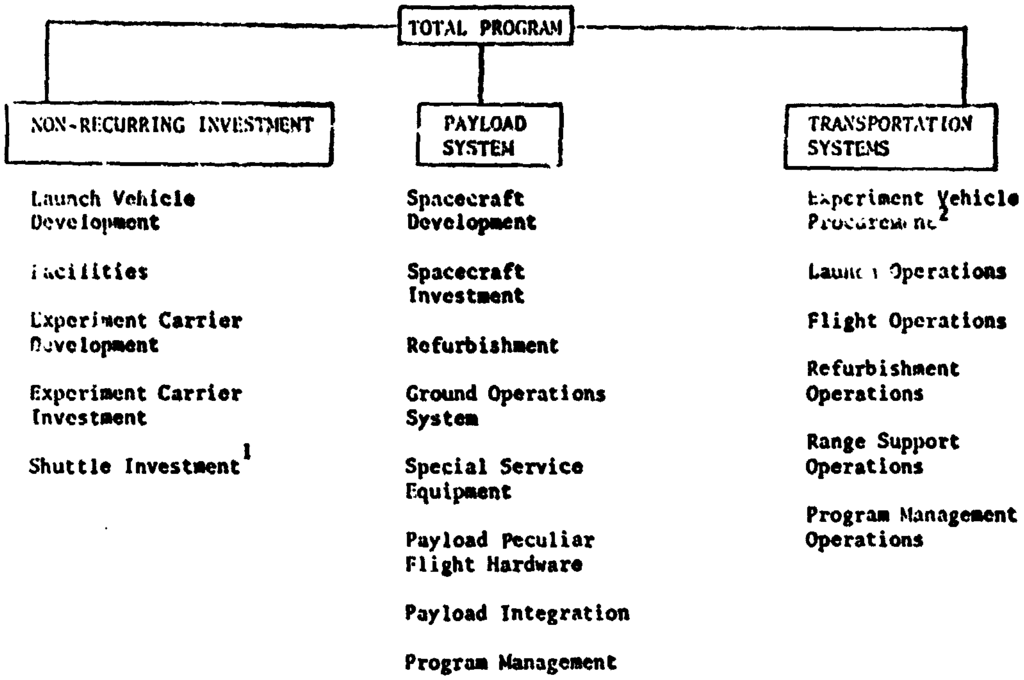
The costs associated with the operation of the Space Shuttle may be broken down into two groupings. Fixed costs reflecting non-recurring development and investment expenditures relating to the Space Shuttle and the fixed and variable costs associated with the operation of the SSTS.

Fixed costs are expenditures that do not vary with the level of operations and variable costs are expenditures that vary with the level of Shuttle activity. Figure 2-1 depicts the catagories of costs used in this report. An analysis of the SSTS costs is given first because it is clear that they must be recovered through user charges levied on commercial space material processing activities. All or some portion of the non-recurring investment charges associated with the procurement and possibly with the development of the Orbiters and the launch facilities for the Orbiter should also be included if the capital investment is to be amortized over the 12 year planning period. Since this analysis assumes that SSTS users are private firms (both foreign and domestic) these non-recurring costs should also be charged to the user. Failure to do so would involve subsidization of Space Shuttle users by the amount of the unallocated site preparation costs and investment costs of the Orbiter. A case can be made for not charging the (full) development costs of the Orbiter to users over the planning period. It is certain that the Orbiter would have been developed in the absence of any commercial space material processers and for this reason the Orbiter development costs can be reasonably treated as nonrecoverable expenditures.

The payload systems shown in Figure 2-1 will not be considered in this section. This element of the SSTS's costs refers to the Spacelab or to the Space Materials Processing Facilities to be used in near-zero gravity environments.

2.4 Calculation of Operating Costs

The base line cost per flight of $10.45 million (1971 dollars) for a total of 439 flights does not include any procurement costs of the Orbiters or any development costs and reflect the following elements [7]:



NOTES:

[1]Does not include Department of Defense spending for the Shuttle.

[2]Does not include Orbiter procurement.

FIGURE 2-1: TOTAL PROGRAM ELEMENTS FOR THE SPACE SHUTTLE TRANSPORTATION SYSTEM

Solid Rocket Booster	$4.28 million
External H_2/O_2	2.31 "
Program Support	1.76 "
Orbiter Spare Parts	1.40 "
Ground Operations	.27 "
Main Engine	.23 "
Fuel & Propellants	.20 "
TOTAL	10.45 "

The cost of $2.31 million per flight for the external tank assumes that the production and maintenance of the external tank will show an 85% increase in efficiency with each doubling of production over the 12 year time period. The assumption relating to the external tank is that only those tanks needed to meet the operational requirements of the traffic model will be required at the launch site. The costs associated with the external tank are:

(a) production costs for the required tanks
(b) spare parts
(c) transportation costs for the tank from the Michould Facility to the launch site
(d) facility maintenance at Michould
(e) computer operations at Slidell.

The cost of $4.28 million per flight for the Solid Rocket Booster assumes 20 flights per motor (or 19 reuses) and a 90 day turn around time from splash down through the refurbishment process to delivery to the launch site. A four percent attrition rate is assumed with 9 refurbishments per lost motor. Only the Solid Rocket Boosters needed to meet operational requirements will be at the launch site. The actual costs included in this are:

(a) production costs
(b) refurbishment costs
(c) spare parts
(d) new recovery parachutes
(e) transportation costs for initial and refurbished components to and from the launch sites from the Michould facility
(f) all costs associated with monitering of the contractors performance at the Michould facility.

The flight cost for Orbiter Spare Parts amounts to $1.40 million and reflects only hardware used in the program. This cost does not include the labor and installation costs of Orbiter components and parts.

2.5 Ground Operational Costs

The cost of ground operations amount to $.27 million per flight. This estimate includes all manpower costs associated with the support of the Shuttle system (Orbiter, Space Shuttle Main Engine, Solid Rocket Booster, and External Tank) as well as the manpower necessary for retrieval. These costs include:

(a) personnel necessary for the performance of unique Solid Rocket Booster retrieval tasks
(b) all launch site based contractor personnel supporting the elements of the Shuttle
(c) refurbishment of Solid Rocket Booster retrieval parachutes
(d) the final installation, assembly and check out of the Solid Rocket Booster performed at the launch site.

The cost per flight of the main engine element is $.23 million. The costs included in this estimate are:

(a) spare parts
(b) major overhaul
(c) transportation costs between contractors facility and the launch sites
(d) Space Shuttle Main Engine test support through FY82
(e) propellants and gases used in acceptance testing of overhauled Space Shuttle Main Engines
(f) Space Shuttle Main Engine GSE provisioned space parts.

Finally the cost of fuel and propellants per flight is estimated at $.20 million. This cost includes the cost of all consumable fuels and propellants and the transportation cost of movements of fuel from the producer to the launch sites.

It should be noted that the average cost of $10.45 million for 439 flights assumes one launch site only. The use of two launch sites would decrease the cost of flying the Shuttle missions now proposed. The assumption of two sites reduces the cost per flight of 439 flights to $9.06 million.

2.6 Methodology

The method developed to establish the costs used in this study involves estimating expenditures for particular elements of the Shuttle System. These costs are based on parametric estimating techniques and do not reflect detailed engineering estimates which would be used in establishing actual budget requests. In addition, adjustments were made in the cost estimates to take into account productivity improvements that occur over time. The productivity improvements referred to here are not related to improved technology but rather reflect increases in efficiency brought about through the routinization of production activities. This kind of productivity improvement is characteristic of the aircraft and space industries and for this reason costs estimates were adjusted to take into account this learning process. Learning curves of different degrees were used in adjusting cost data for increases in efficiency. For the base line flights referred to earlier, an 85 and 95 percent learning curves were used. An 85 percent learning curve means that the cumulative average costs are reduced at a constant rate (85 percent of their previous level) each time output doubles. In the case of a 100 percent learning curve costs would not be altered as a result of "learning" as output is doubled. In this study costs were calculated on the basis of several learning curves.

This study will assume that only the Florida site will be used in space processing. The use of both the western and eastern launch sites would be associated with lower costs per flight. However, it is assumed that most of the space processing flights will be low orbit flights. The Florida launch site at Cape Kennedy would seem to be the appropriate operational base for space processing activities. The high density traffic orbit for the October 1973 Shuttle traffic model is 220 nautical miles with a 28.5 degree inclination.

2.7 Total Cost Curves

To determine the effect of different levels of Shuttle activity on the average costs of operation of the SSTS total, the average cost curves for the 12 year planning period were calculated on the basis of the following levels of Shuttle activity:

Total Flights:	144	240	360	480	672	720	840	984
Flights Per Year:	12	20	30	40	56	60	70	82

The total number of flights were assumed to be distributed evenly over the 12 year planning period for each of 8 levels of activity. Average annual total costs for each activity level were calculated and curves were fitted to these points (see Figure 2-2). Average annual total costs were discounted using 0, 5, 10 and 15 percent discount rates. The discounting process allows economic alternatives at 0, 5, 10 and 15 percent to be taken into account in calculating costs for the 12 year planning period. The various hypothesized levels of Shuttle activity involve the committing of resources to the space program rather than to other uses. The costs of these resources should be discounted to take into account the return on these forgone opportunities.

In summary the total costs per flight of the Shuttle system are dependent

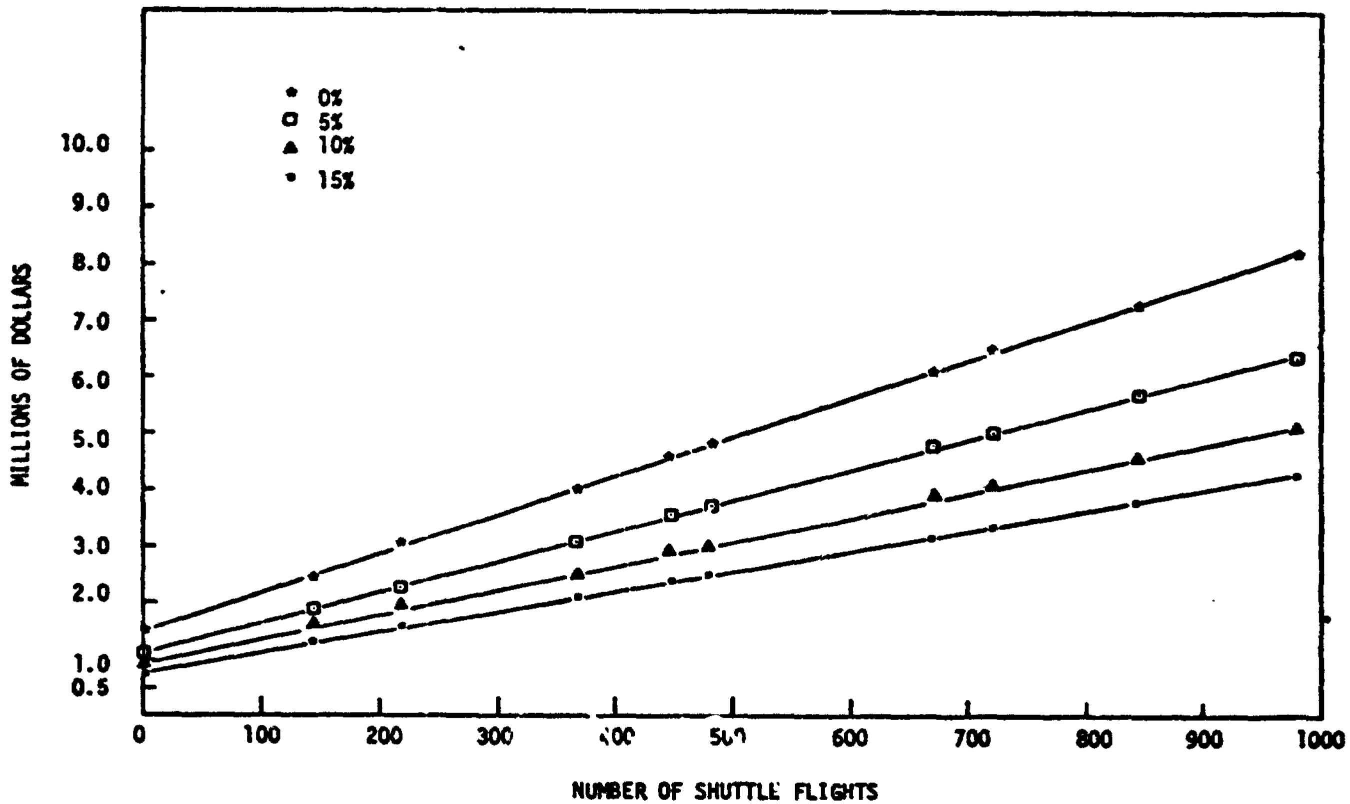


FIGURE 2-2: SPACE SHUTTLE TOTAL COST CURVES BASED ON THE OCTOBER 1973 TRAFFIC MODEL FOR 0, 5, 10, & 15 PERCENT DISCOUNT RATES

upon a number of variables including those listed below:

(a) orbit elevation
(b) number of launch sites
(c) learning curve
(d) number of flights
(e) the discount rate
(f) flight distribution over the 12 year period.

In this study only factors (d) and (e) are allowed to vary. The number of flights and the discount rate are the most critical values for an economic analysis of space material processing activities (see Figure 2-2).

In this study the SSTS costs will be discounted at zero, five, and ten percent discount rates. An explanation of the choice of the discount rates is included in Appendix 2-I.

2.8 Calculations

The total costs of the SSTS will vary greatly with the level of flight activity undertaken over the 12 year planning period. Table 2-1 relates total average and marginal costs for levels of flight activity ranging from 12 to 82 flights per year. The presently planned inventory of equipment for the SSTS limits shuttle activity to about two flights per week as a maximum. Table 2-1 shows cost calculations in terms of 1971 dollars over the 12 year period for different levels of Shuttle activity. The costs in this table are not discounted.

The second degree total cost curve has the following form:

(1) $TC_0 = 1298.391 + 7.899\ X - .0001\ X^2$ where,

TC_0 = total costs not discounted and in millions of 1971 dollars

X = total number of flights.

Since the total cost surve is approximately linear, the marginal or incremental cost for each additional flight is nearly constant and equal to about $7.810 million for 445 flights. Fixed costs are approximately $1298.391 million.

It should be noted that the maximum weight of the Space Shuttle differs for the launch and return phases of the flight. The Shuttle has a maximum cargo launch weight of 65,000 lbs., however, the return cargo weight maximum for the vehicle is only 32,000 lbs. If we assume a 12 year level of activity of 37 flights per year the cargo payload cost per pound for a launch would be $326.

Discounting the average annual costs associated with the different levels of Shuttle activity using a 5 percent interest rate produces a discounted total cost curve that has the form:

$TC_5 = 999.6052 + 6.0874\ X - 0.0006\ X^2$ where,

TC_5 = total cost discounted by 5 percent and in millions of 1971 dollars

X = total number of flights.

In this case the discounted fixed cost is $999.6 million and the marginal cost per flight is approximately $5.6 million for 445 flights. The data upon which the 5 percent Discounted Total Cost Curve is based is shown in Table 2-2.

The discounted average cost per pound for a 5 percent interest rate for 445 flights is $253 per pound.

The 10 percent Discounted Total Cost Curve has the form:

$TC_{10} = 765.6162 + 5.1032\ X - 0.0007\ X^2$ where,

TC_{10} = total cost discounted by 10 percent and in millions of 1971 dollars

X = total number of flights.

The above equation is based on data found in Table 2-3. Using a 10 percent discount rate fixed cost is $765.6 million and the marginal cost per flight is about $4.48 million for 445 flights. The discounted average cost per pound for a 10 percent interest rate for 445 flights is $203.

TABLE 2-2: SPACE SHUTTLE COST ESTIMATES FOR SELECTED LEVELS OF FLIGHT ACTIVITY AND A FIVE PERCENT DISCOUNT RATE FOR A 12 YEAR PLANNING PERIOD[4]

ANNUAL FLIGHTS	12 YEAR TOTAL FLIGHTS[1]	AVERAGE COST PER FLIGHT[2] ($1,000,000)	TOTAL COST ($1,000,000)	MARGINAL COST PER FLIGHT ($1,000,000)	TOTAL CARGO (1000 lbs.)[3]	COSTS PER POUND ($)
12	144	12.960	1866.323	5.9146	4608	405
20	240	10.169	2440.669	5.7994	7680	317
30	360	8.614	3100.952	5.6554	11520	269
37	445	8.086	3598.280	5.5534	14208	253
40	480	7.874	3779.474	5.5114	15360	245
56	672	7.157	4809.199	5.2810	21504	223
60	720	7.005	5043.270	5.2234	23040	218
70	840	6.756	5674.703	5.0794	26880	211
82	984	6.476	6372.023	4.9066	31488	202

NOTES:

(1) 12 year planning period
(2) 200 N.M. orbit, 28.5° inclination
(3) 32,000 lb. cargo load
(4) 1972 Dollars

SOURCE:

Estimates shown in column 3 were obtained from Mr. H.C. Mandell and Mr. John Wise of the Space Shuttle Resource Management Office, NASA, Houston.

TABLE 2-3: SPACE SHUTTLE COST ESTIMATES FOR SELECTED LEVELS OF FLIGHT ACTIVITY AND A TEN PERCENT DISCOUNT RATE FOR A 12 YEAR PLANNING PERIOD[4]

ANNUAL FLIGHTS	12 YEAR TOTAL FLIGHTS[1]	AVERAGE COST PER FLIGHT[2] ($1,000,000)	TOTAL COST ($1,000,000)	MARGINAL COST PER FLIGHT ($1,000,000)	TOTAL CARGO (1000 lbs.)[3]	COSTS PER POUND ($)
12	144	10.438	1503.080	4.9016	4608	326
20	240	8.190	1965.639	4.7672	7680	255
30	360	6.937	2497.407	4.5992	11520	216
37	445	6.512	2897.943	4.4802	14208	203
40	480	6.337	3041.870	4.4312	15360	198
56	672	5.763	3873.176	4.1624	21504	180
60	720	5.641	4061.689	4.0952	23040	176
70	840	5.441	4570.225	3.9272	26880	170
82	984	5.215	5131.826	3.7256	31488	162

NOTES:

(1) 12 year planning period
(2) 200 N.M. orbit, 28.5° inclination
(3) 32,000 lb. cargo load
(4) 1972 Dollars

SOURCE:

Estimates shown in column 3 were obtained from Mr. H.C. Mandell and Mr. John Wise of the Space Shuttle Resource Management Office, NASA, Houston.

A 15 percent Discounted Total Cost Curve has the form:

TC_{15} = 705.4653 + 3.9353 X - 0.0003 X^2 where,

TC_{15} = total cost discounted by 15 percent and in millions of 1971 dollars

X = total number of flights.

Table 2-4 presents the data in tabular form upon which this equation is based. Using a 15 percent interest rate fixed cost is $705.5 million and the increase in cost for each additional flight is approximately constant and equal to $3.67 million for 445 flights. The discounted average cost per pound for a 15 percent interest rate for 445 flights is $170.

In order to take into account the alternative case of resources both costs and revenues must be discounted for the 12 year planning period used in this analysis. This analysis assumes that total costs, for each level of activity, will be spread evenly over the 12 year planning period. In this analysis average annual total costs are discounted for each level of SSTS activity. This was done because it was assumed that the Shuttle would be run on a regular operating schedule during the commercial phase of space material processing.

It should be noted, however, that NASA's annual funding requirements in billions of 1971 dollars range from $3.375 billion in 1980 to $2.189 billion in 1990 [8]. Except for 1987 and 1988 NASA's annual funding requirement trends down for every year over the 12 year planning period used for this analysis. This suggests that the discounting of a constant stream of annual expenditure for the whole 12 year period is a conservative estimate of discounted total costs for each level of SSTS activity.

The preceeding cost analysis delt with operating costs of the SSTS. However, these costs do not include the non-recurring investment costs

TABLE 2-4: SPACE SHUTTLE COST ESTIMATES FOR SELECTED LEVELS OF FLIGHT ACTIVITY AND A FIFTEEN PERCENT RATE FOR A 12 YEAR PLANNING PERIOD[4]

ANNUAL FLIGHTS	12 YEAR TOTAL FLIGHTS[1]	AVERAGE COST PER FLIGHT[2] ($1,000,000)	TOTAL COST ($1,000,000)	MARGINAL COST PER FLIGHT ($1,000,000)	TOTAL CARGO (1000 lbs.)[3]	COSTS PER POUND ($)
12	144	8.681	1250.130	3.8489	4608	271
20	240	6.812	1634.852	3.7913	7680	213
30	360	5.770	2077.132	3.7193	11520	180
37	445	5.416	2410.260	3.6683	14208	170
40	480	5.274	2531.631	3.6473	15360	165
56	672	4.794	3221.375	3.5321	21504	150
60	720	4.692	3378.169	3.5033	23040	147
70	840	4.525	3801.125	3.4313	26880	141
82	984	4.338	4268.214	3.3449	31488	136

NOTES:

(1) 12 year planning period
(2) 200 N.M. orbit, 28.5° inclination
(3) 32,000 lb. cargo load
(4) 1972 Dollars

SOURCE:

Estimates shown in column 3 were obtained from Mr. H.C. Mandell and Mr. John Wise of the Space Shuttle Resource Management Office, NASA, Houston.

associated with the SSTS program. These costs include Shuttle investment, experiment carrier development and investment, ground facilities and launch vehicle development. However, the Department of Defense Space Shuttle requirements are excluded from this estimate. The non-recurring investment relating specifically to the shuttle and its associated ground facilities is $7.8 billion.

2.9 Non-recurring Investment and Development Costs

The non-recurring investment and development expenditures will be concentrated in Fiscal Years 1975 through 1980. These are fixed costs that will be incurred regardless of the level of Shuttle operating activity. All or some part of these expenditures should be included in the analysis of the space material processing activities because a commercial operation in space should cover not only operating costs but also should cover the cost of amortizing some part of NASA's Shuttle investment costs.

Table 2-5 presents the maximum non-recurring investment and development expenditures to be allocated to different levels of Shuttle activity for discount rates ranging from zero to 15 percent. These investment costs should be added to operating costs to determine the maximum SSTS costs of operation and capital amortization. If all investment costs are assumed to be made during the initial year of the program, then the investment costs should not be discounted.

However, it should be noted that the $7.8 billion dollars (shown in Table 2-5) primarially reflects development expenditures. The estimated costs of the five NASA Orbiters only and their associated ground facilities amounts to $1345 million. The unit cost of an Orbiter is estimated to be $250 million. For purposes of calculating the minimum costs of operating and

TABLE 2-5: SPACE SHUTTLE NON-RECURRING DEVELOPMENT AND INVESTMENT EXPENDITURES DISCOUNTED AT A 0 PERCENT INTEREST RATE[1]

ANNUAL FLIGHTS	12 YEAR TOTAL FLIGHTS	AVERAGE COST PER FLIGHT ($1,000,000)	TOTAL COST ($1,000,000)	TOTAL CARGO (1000 lbs.)[2]	COST PER POUND ($)
12	144	53.9	7756	4608	1683
20	240	32.3	7756	7680	1010
30	360	21.5	7756	11520	673
37	445	17.4	7756	14208	546
40	480	16.1	7756	15360	506
56	672	11.5	7756	21504	361
60	720	10.7	7756	23040	337
70	840	9.2	7756	26880	289
82	984	7.8	7756	31488	246

NOTES:

(1) At a 0% discount rate total non-recurring Shuttle development and investment costs would be $7,756 million.

(2) The Orbiter has a cargo payload capacity of 32,000 lbs.

SOURCE:

Shuttle Utilization Planning Office, "The October 1973 NASA Mission Model Cost and Economic Analysis," Marshall Space Flight Center, NASA Technical Memorandum 64802, January 1974.

TABLE 2-6: AVERAGE ANNUAL TOTAL COST FOR DIFFERENT LEVELS OF SPACE SHUTTLE ACTIVITY IN 1972 DOLLARS

ANNUAL FLIGHTS	AVERAGE ANNUAL TOTAL COST ($1,000,000)
12	200.544
20	262.260
30	333.210
37	386.650
40	406.120
56	516.768
60	541.920
70	609.770
82	684.700

amortizing the SSTS over the 12 year planning period, non-recurring development expenditures associated with the Orbiter, Department of Defense investment in Orbiters, Space Tug development and investment expenditures, and Spacelab expenditures for development and investment are excluded from this analysis.

In this minimum cost analysis only the non-recurring investment costs of the Orbiter and its support ground facilities are included as fixed elements of transportation costs of the SSTS. Only $1345 million is included as capital amortization of the SSTS. This outlay will not be discounted as it is assumed that this investment spending will be made at the beginning of the planning period. The average cost per pound incurred for the recovery of the non-recurring investment expenditures charged to the SSTS for Space processing activities would be $42 for a 82 flight per year level of Shuttle activity. Cost data for the Orbiter and associated ground facility investment is given in Table 2-7.

The minimum total operating and amortization costs charged to the SSTS for purposes of calculating total cost of the SSTS, as it relates to space processing (for a 5 percent rate of discount), are given in Tables 2-3 and 2-7 of this section of the report. Assuming a level of SSTS activity of 82 flights per year, the operation cost net of Orbiter and related facility investment would be $202 per pound of cargo payload. The minimum total operating and capital amortization costs of the SSTS, as it relates to material space processing, would be $244 per pound of cargo payload. If the full costs of amortizing all development expenditures associated with the SSTS was taken into account the maximum charge per pound, at 5 percent discount rate and 82 flights per year would be $246. The corresponding

TABLE 2-7: AVERAGE COSTS OF NON-RECURRING INVESTMENT OF THE ORBITER AND ASSOCIATED GROUND FACILITIES TO BE CHARGED AGAINST THE SSTS AS CAPITAL AMORTIZATION OVER THE 12 YEAR PLANNING PERIOD[1]

ANNUAL FLIGHTS	12 YEAR TOTAL FLIGHTS	AVERAGE COST PER FLIGHT[1] ($1,000,000)	TOTAL COST ($1,000,000)	TOTAL CARGO (1000 lbs.)[2]	COST PER POUND ($)
12	144	9.340	1345	4608	292
20	240	5.604	1345	7680	175
30	360	3.736	1345	11520	117
37	445	3.022	1345	14208	95
40	480	2.802	1345	15360	88
56	672	2.001	1345	21504	62
60	720	1.868	1345	23040	58
70	840	1.601	1345	26880	50
82	984	1.367	1345	31488	43

NOTES:

(1) Total non-recurring investment expenditures charges to the SSTS for materials processing activities is $1345 million.

(2) The Orbiter has a cargo payload capacity of 32,000 lbs.

SOURCE:

Shuttle Utilization Planning Office, "The October 1973 NASA Mission Model Cost and Economic Analysis," Marshall Space Flight Center, NASA Technical Memorandum 64802, January 1974.

maximum costs of operating and amortization of the SSTS would be $448 per pound of cargo payload. It should be noted that since the cost streams involved here are to be undertaken by the public sector, the appropriate ratio would probably fall somewhere between 5 and 10 percent. It would also appear reasonable to assume a high level of space activity, perhaps 82 flights per year. Since the development cost of this Orbiter would have been incurred regardless of whether space processing velocities are undertaken or not it would seem reasonable not to include the $246 of development costs in the cost per pound calculations. That is, using the above assumptions, a minimum total operating, and capital amortization costs of the SSTS of $244 would appear to be appropriate.

The cost allocations to space material processing activities for purposes of determining minimum operating and amortization costs of the SSTS are based on the proportion of cargo payload capacity of the Orbiter required by the user. However, this is only one of several ways that might be used to make such cost allocations. We are assuming in this paper that joint transportation services are produced by the operation of the SSTS. The Orbiter will be used for near-zero gravity experimental work in space and some residual payload capacity will be available for materials processing in space. The question naturally arises as to what user charges will be made for space material processing activities.

The method of allocating joint costs to multiple activities or uses recommended by the Engineers Joint Council suggests that joint costs be allocated on the basis of the proportionate use of capacity.[9] The proportionate use of capacity method of allocating costs has been used in this analysis as a first attempt at calculating costs of the SSTS to specific space processing activities. This method has defects, however, in that it ignores the benefits generated by the respective users. It may be argued that a user charge ought to take into account the ability to pay of the user, which in turn reflects the benefits to the user of space materials processing. In this analysis the proportionate use of capacity is simply employed as a rough guideline to allocating costs to all space material process users on the basis of the cost per pound of cargo movements. This is not to say that the user charges should be fixed in this way.

The economic approach to fixing user charges suggests that benefits of the activity ought to be taken into account on pricing the SSTS transportation service. A generally accepted method of cost allocation used to fix user charges is the specific costs-remaining benefits principle. In this approach all specific costs that relate to a particular use are charged against that use, and netted out of the benefits associated with that use. The user benefits are calculated net of the alternative costs of earth based production. If no alternative for space production exists on earth then the user benefits are taken net of any specific costs. Joint cost are allocated proportionately to the net benefits of the space processing users.

2.10 References

1. Shuttle Utilization Planning Office, "The October 1973 Space Shuttle Traffic Model," Marshall Space Flight Center, NASA Technical Memorandum 64751, January 1974.

2. Committee on Science and Astronautics, "Space Shuttle, Space Tug, Apollo-Soyuz Test Project-1974," U.S. House of Representatives, 93 ed. Congress, 2 ed. Session (Washington: GPO, February 1974), p. 54.

3. Interium Spacelab Reference Document, Spacelab Program Office, George C. Marshall Space Flight Center, April 18, 1974.

4. Unpublished memorandum from the Director, Space Lab Program to the Director, Engineering and Operations data, June 6, 1974.

5. Shuttle Utilization Planning Office, "The October 1973 NASA Mission Model Cost and Economic Analysis," Marshall Space Flight Center, NASA Technical Memorandum 64802, January 1974, p. 16.

6. Committee on Science and Astronautics, "Space Shuttle, Space Tug, Apollo-Soyuz Project-1974," U.S. House of Representatives, 93 ed. Congress, 2 ed. Session (Washington: GPO, February 1974), p. 539.

7. Unpublished material, presentation of Space Shuttle Costs per Flight to the General Accounting Office, December 1973.

8. Committee on Science and Astronautics, "GAO Report on Analysis of Cost of Space Shuttle Program," U.S. House of Representatives, 93 ed. Congress, 1st Session (Washington: GPO, June 26, 1973), p. 60 in Appendix II.

9. O.C. Herfindahl and Allen V. Kneese, Economic Theory of Natural Resources, Columbus: Charles E. Merrill Publishing Company, (1974), 290-294.

2.11 APPENDIX

The present value of the cost stream associated with the SSTS may be given by the following statement:

(a) $PV_0 = \frac{1}{(1 + r)^n} C$ where we have a cost, C, occurring periodically for n time periods at a discount rate of r. However, we want to access the present value of a stream of income that goes on every moment of time. A statement of this continuous movement can be developed in the following way.[1] We define a number, e, as the limit of the expression $(1 + \frac{1}{n})^n$ as n approaches infinity. A cost stream, C, invested for n years at a rate of interest, r, with continuous compounding yields a present value of:

(b) $PV_0 = e^{-rn} C_n$, where C = 2.718.

The PV_0 of the cost stream will be sensitive to changes in the discount rate as shown below:

(c) $\frac{d\ PV_0}{dr} = -ne^{-rn} C_n$.

In order to evaluate the impact of a stream of expenditures taking place over a period of time the cost should be discounted for two reasons. Individuals may prefer current consumption to future consumption; therefore, any expenditure that detracts from consumption, present and future ought to be discounted. Secondly, the generation of any stream of expenditures is associated with an opportunity cost. If capital funds are limited spending for one project means the sacrifice of some other activity, either in the public or private sector. In calculating a discount rate both reasons for discounting are usually taken into account. The exact mix of these two forces are usually weighted according to the source of funds used to finance the cost stream--that is the funds way have been drawn from consumption, savings, or may reflect user changes and therefore ought to perhaps be associated with different discount rates. The actual discount rates that are normally used reflect observed market interest rates.

The appropriate rate of discount for evaluating the stream of Space Shuttle costs depends upon the method of financing NASA expenditures. It is assumed that the costs of operating the SSTS will be drawn from several sources (a) user charges, (b) tax revenues (drawn ultimately from consumption and saving), and (c) bond sales. Table 2-A-1 shows a possible revenue pattern that might be used to finance the operation of the SSTS.

TABLE 2-A-1: REVENUE PATTERN AND INTEREST RATES APPROPRIATE FOR DISCOUNTING THE COSTS OF OPERATING THE SPACE SHUTTLE TRANSPORTATION SYSTEM

Possible Relative Revenue Pattern (Weight)			Source of Revenue	Appropriate Interest Rate
20			User Charges	Bank Prime rate
80			Government Sector	
	(92)		Taxes	
		(93)	Consumption	Social rate of discount[1]
		(07)	Savings	5 year consumer certificate of deposit
	(08)		Government Securities	Federal government long term bond rate
100	100	100		

NOTE:

(1) The social rate of discount is given by $r = (1 + \frac{k-n}{1+n})^e - 1$, where n is the rate of population growth, k is the rate of growth of total consumption and e takes on a value of approximately 2. A discussion of the social rate of discount, r, is given on A.K. Dasqupta and D.W. Pearch, Cost-Benefit Analysis (London: The Macmillan Press, 1972), pp. 141-144.

2.12 Footnotes: Appendix

1. William J. Baumol, Economic Theory and Operations Analysis, 3rd Edition, Englewood Cliffs: Prentice-Hall, Inc., (1972), p. 449.

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3. COSTS AND BENEFITS OF TURBINE BLADES

3.1 Introduction and Summary

The purposes of this study are:

a. To determine if suitable demand for a space processed turbine blade will exist and estimate the extent of demand for the period 1980-1992.

b. To estimate the dollar benefits to be derived from incorporation of such an advanced technology turbine blade. The technological assumptions utilized for this study are:

   1. For existing aircraft, an added 200° temperature tolerance from the space processed blade with average blade life doubled and fuel consumption reduced by 4%.

   2. For new aircraft the increased efficiency will be incorporated in increased thrust of 10% and increased payload of 20%.

c. To provide a reasonable estimate of some of the costs of production that may be expected under space processing procedures.

d. To determine if turbine blades are a likely candidate for space processing.

e. To examine some of the possible technologies for space production of turbine blades and indicate where technological development is needed. This portion of the study is presented separately in Section 4.0.

3.1.1 Findings

a. There will be an adequate demand to justify production of space processed blades both from a quantity and benefits derived standpoint. Quantities demanded (Table 3-5, Col. 6) could begin in 1980 at 121,987 for five years and rise after that for U.S. commercial airlines alone. For data purposes this study was confined to the potential demand from U.S. commercial airlines. When other users and applications are considered these figures could be considerably larger, perhaps by three times as much or more. Economies of scale may reduce the costs anticipated in this study as additional space factories are put into operation.

b. The benefits for use of the space processed blade are computed to be $991.50 per blade over its anticipated 7.5 year lifetime when utilized as replacement blades in existing aircraft. For new aircraft, which could be designed to fully utilize the technological advances with increased payload capacity, the value per blade would be over $21,000 over the 7.5 year lifespan.

c. A residual factory cost, which tells the maximum allowable amount that could be invested in the development, launch, and direct operational costs of the space factory was computed under three separate assumptions:

1. Assuming the transport weight of the mold, rack and remelt blade materials to be 1.5 lbs. (680.4 gm.) per blade, the residual factory cost would be $369,482,727. This estimate is regarded as the best weight estimate.

2. Assuming the transport weight of the mold, rack and remelt blade materials to be 2 lbs. (907.2 gm.) per blade, the residual factory cost is $113,428,182. This estimate is regarded as a high weight estimate.

3. Assuming the transport weight of the mold, rack and remelt blade materials to be 1 lb. (453.6 gm.) per blade, the residual factory cost is $625,540,909. This estimate is regarded as a low weight estimate. However, by substituting a manned operation, such that permanent molds are kept at the factory this weight may be feasible. If so, a differential of $256,058,182

for purposes of manned operation would be available over the best weight estimate. For the heavy weight estimate $512,116,364 would be freed for manned operations.

d. The total dollar savings to U.S. commercial airlines for 100% adoption (over a ten year period) would be 4.381 billion dollars for the 10 year period 1980-1989. For the 13 year period 1980-1992 this figure would be 6.618 billion dollars.

e. Substantial fuel savings would be realized. Per year saving in fuel use would 111.7 million gallons in 1981 and rise to 990.4 million gallons by 1992 using the adaption schedule assumed. For the 12-year period (1981-1992) the fuel savings would amount to 6.522 billions of gallons of jet fuel. This savings is all the more important in light of the recent and continuing energy crisis. In addition, the importation of oil creates serious problems for the U.S. balance of payments. Any reduction of fuel consumption levels from what would have been generated desirable movements in the balance of payments position of the U.S.

f. Turbine blades for aircraft appears to be a viable candidate for space processing providing that the product can be manufactured to provide the assumed technological advance. Development, launch and direct operational costs could exceed $369 million dollars (best estimate) and produce with a reasonable return on investment.

g. Calculations contained herein are based on a potential selling price of $991.50 for the turbine blade. This is the price for new aircraft blades as well as replacement blades. Should space manufacturing prove unfeasible for replacement blades, two alternatives remain that would still make space processing of turbine blades potentially feasible:

1. The appreciably higher value for new aircraft blades would make possible price discrimination between new aircraft blades and replacement blades. A higher than cost price could be charged for new aircraft blades, subsidizing a lower than cost price for replacement blades.

2. Production could be limited to blades for new aircraft only. In this event, the likelihood of a much higher rate of replacement for existing aircraft is high, since the potential savings from newer aircraft would be large.

3.2 Analysis of Potential Demand

3.2.1. Introduction

For the manufacturing of turbine blades in space to be economical, several conditions must be met:

a. The blades must have a high value relative to the blades currently in use, since the cost of manufacturing such blades will be several times larger than the earth processed blades.

b. A need for relatively large quantities should be demonstrated.

c. Costs, which will be borne by the producer must be less than the benefits to the potential buyers.

The present study will estimate the total potential demand for turbine blades of the commercial airline fleet of the United States beginning with the year 1980 and ending with 1992. The premise involved is that if sufficient demand can be generated from this source alone, the total demand will be merely some multiple of the sufficient demand but have no further bearing on the feasibility of the production.

The following assumptions are used in the computations:

a. Average blade life--9000 hours for conventional blades [1].

b. Average blade life--18000 hours for space processed blade

c. Engines of the class JT8D-7 (Pratt and Whitney) are utilized for all turbine jets not classified as "jumbo" jets

d. Space processed blades for JT8D-7 engines are required only for the 1st stage of the high pressure turbine. (80 blades per engine)

e. Engines of the class JT9D (Pratt and Whitney) are utilized for all "jumbo" jets

f. Space processed blades for JT9D engines are required for 1st and 2nd stages (both air cooled) of the high pressure turbine (116 and 138 blades respectively) [2].

g. The average blade is assumed to weigh 6.75 ounces (191.36 gms). This is the approximate weight of the 1st stage turbine blade currently used in the JT8D engine. Realistically, blades of varying sizes and weights will be required to make production feasible. This blade was chosen to simplify estimates because it represents a large portion of the blades currently in use that are potential candidates for space processing.

h. The average engine time use is 200 hours per month.

i. Replacement of existing blades begins in 1980 with a replacement rate of 10% per year of the existing stock of blades in use. By the year 1990 all commercial aircraft are assured to utilize space processed blades.

j. When space produced blades wear out, they are replaced by space processed blades.

k. The projected rate of growth of engines in use is very modest. The projections made by the Federal Aviation Agency [3] are utilized until 1981. Beyond 1981 the number of engines in use was assumed to increase linearly and projected foward to 1992. The rate of increase of engines in use is 3.0% for 1982 and decreases mildly each year to 2.59% in 1991.

l. Production costs are absorbed by the producer. As such he normally must be able to recover these costs in direct benefits in production. These benefits may take the form of added revenue or lower costs in some other area. For purposes of this study we shall examine only the direct benefits to the airline industry and assume that they are willing to pay to receive these direct benefits.

   This study is designed to estimate the full costs and benefits of the space production of turbine blades. As such, it assures that space processed turbine blades will be processed only if they are sold at a price that fully recovers costs. This approach has one distinct advantage.

   The advantage is that the procedure estimates whether production under private enterprise could be commercially feasible, if NASA were fully reimbursed for transport costs of the operation. Under such a plan the full costs of building, launching, and operating a space factory would be borne by the commercial producers. No subsidy is provided for production.

   Should some subsidy of an operation be desired, costs to the producer would be further reduced. Such a subsidy would probably be most likely in the form of space available on certain scheduled flights. However, this approach has one major drawback. At the levels of anticipated demand outlined in this study, space available would not likely be sufficient to provide transportation for the turbine blade space operation. Hence, special flights would be necessary in any case. Otherwise, sufficient production levels could not be maintained to meet demand, creating a rationing problem. The view taken in this study is that space available on scheduled missions could more beneficially be used biological or crystal producers.

3.2.2 Methodology

The methodology followed in this study is outlined by the Figures 3-1 through 3-7.

a. The primary assumptions are given by Figure 3-1.

b. Figure 3-2 outlines the method used to obtain the figures for total turbine blades in use. The primary source of original data is the Federal Aviation Agency's Aviation Forecasts for Fiscal Years 1975-1986. These figures were extended to 1992 by assuming that the last two years (1985 and 1986) differential would be continued until 1992. This is a linear extension from the last two years. It was further assumed that the percent of jumbo jets would be 21%. This allowed computation of the total number of turbine blades in use as presented in Table 3-3. All of these computations were made assuming no space processed blades were produced.

   A second set of computations, given in Table 3-4, was then calculated that assumed production of space processed blades. Since payload is assumed to increase 20%, the number of new aircraft was also reduced by 20%. Computations were similar beyond this point to calculations for Table 3-3.

c. Figures 3-3A and 3-3B show the elements used to calculate total potential demand. Three separate computations were made and summed: (1) Blades for newly produced aircraft (new plane blades) (Figure 3-3A), (2) Replacement blades to replace earth produced blades in existing aircraft, and (3) Replacement blades to replace space processed blades when they wear out. The wearout rates for space processed blades were assumed to average 7.5 years and have a wearout distribution as shown in Figure 3-8. The sum of these three elements yield total potential demand. These computations are presented in Table 3-5, and the total potential demand figure is plotted in Figure 3-9.

d. Figure 3-4 shows elements used to calculate the benefits of using space processed blades. Four factors were considered: (1) Fuel economies realized from operating fewer aircraft with the same payload (calculated for new post-1980 aircraft only), (2) Fuel economies realized by existing aircraft converting to space processed blades, (3) A capital saving from purchasing fewer aircraft with the same payload capacity, and (4) An operational saving from fewer flights. These calculations are made in Tables 3-8, 3-9, and 3-10.

e. Figure 3-5 displays the various types of costs considered.

f. Figure 3-6 shows the format used to estimate the maximum capital outlay bearable under the estimated costs and benefits for development construction and launch of a space processing facility with an expected life of 10 years. Total Variable Costs included are: (1) shuttle or transportation costs, (2) materials and earth operation costs, and (3) Overhead and Administrative Costs. Fixed Costs are not directly estimated but left as a residual to be calculated when other factors are known, and allowing a 10 percent return on investment. Setting total costs equal to total anticipated revenues, yields one equation and one unknown (factory costs). Solving this equation yields the maximum allowable factory costs.

g. Figure 3-7 is brief statement of conclusions.

* BLADE LIFE: 9000 HOURS FOR CONVENTIAL BLADE

  18000 HOURS FOR SPACE PROCESSED BLADES (SPB)
* SPB FOR STAGE 1 (HP TURBINE) JT8D-7 (80 BLADES / TURBINE)
* SPB FOR STAGE 1 AND 2 OF JT9D (JUMBO) (254 BLADES / TURBINE)
* ENGINE USAGE - - 200 HRS / MONTH
* 10 PERCENT OF BLADES REPLACED / YEAR BEGINNING 1980 (10 YEAR FULL CONVERSION TO SPB)
* FAA PROJECTIONS EXTENDED LINEARLY FOR AIRCRAFT IN USE AND FUEL CONSUMPTION
* BLADE WEIGHT - - 6.75 OZ. (191.36 GMS)
* TOTAL WEIGHT FOR TRANSPORT - - 1½ LB. (680.4 GMS)
* SPB PROVIDE 10% INCREASE IN THRUST WITH 20% INCREASE IN PAYLOAD INSTALLED IN NEW AIRCRAFT
* SPB PROVIDE 4% DECREASE IN FUEL USE WHEN INSTALLED IN EXISTING AIRCRAFT

FIGURE 3-1: ASSUMPTIONS

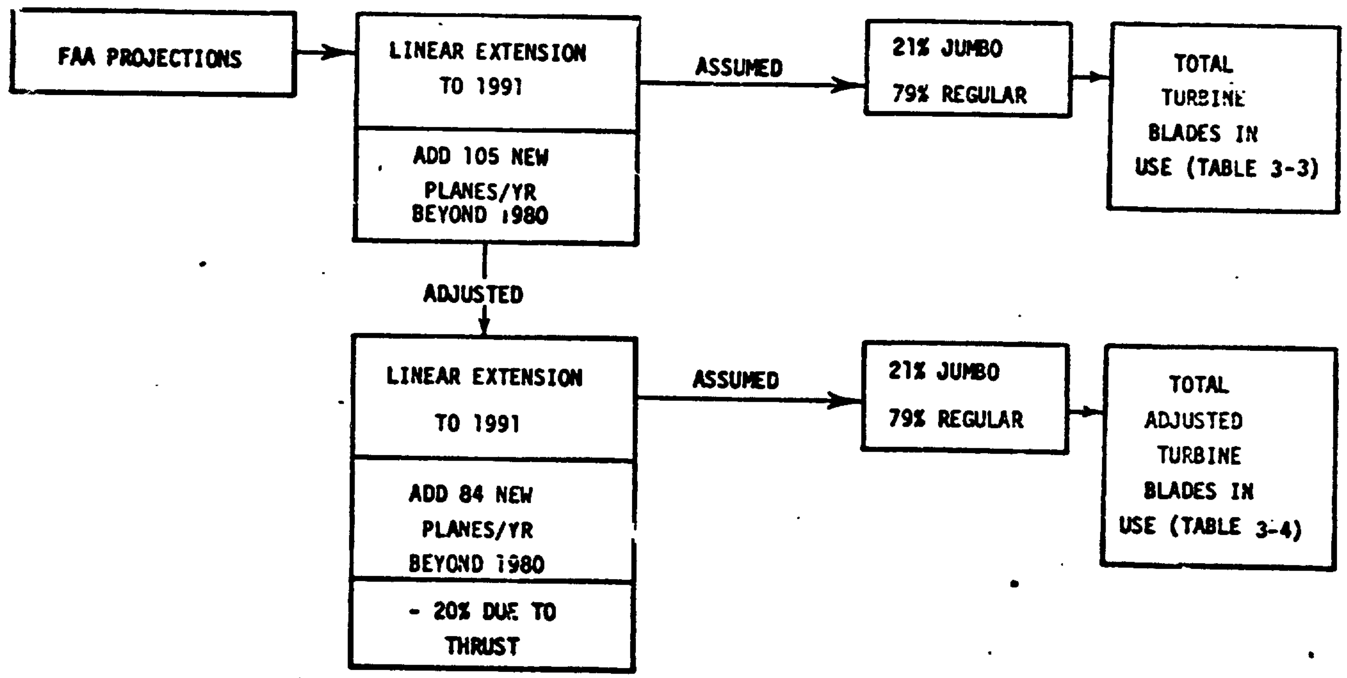

FIGURE 3-2: PROJECTIONS OF TOTAL TURBINE BLADE USAGE

(1)

6	4-ENGINE AIRCRAFT X 4 =	24 TURBINE ENGINES
56	3-ENGINE AIRCRAFT X 3 =	168 TURBINE ENGINES
22	2-ENGINE AIRCRAFT X 2 =	22 TURBINE ENGINES
84		236 TURBINE ENGINES

(2)

236 X .21 = 50 JUMBO ENGINES / YEAR

266 X .79 = 186 REGULAR ENGINES / YEAR

(3)

50 X 254 = 12,700 BLADES FOR JUMBO ENGINES

186 λ 80 = 14,880 BLADES FOR REGULAR ENGINES

TOTAL 27,580 BLADES FOR ALL NEW ENGINES

FIGURE 3-3A:

CALCULATION OF NEW PLANE BLADES NEEDED

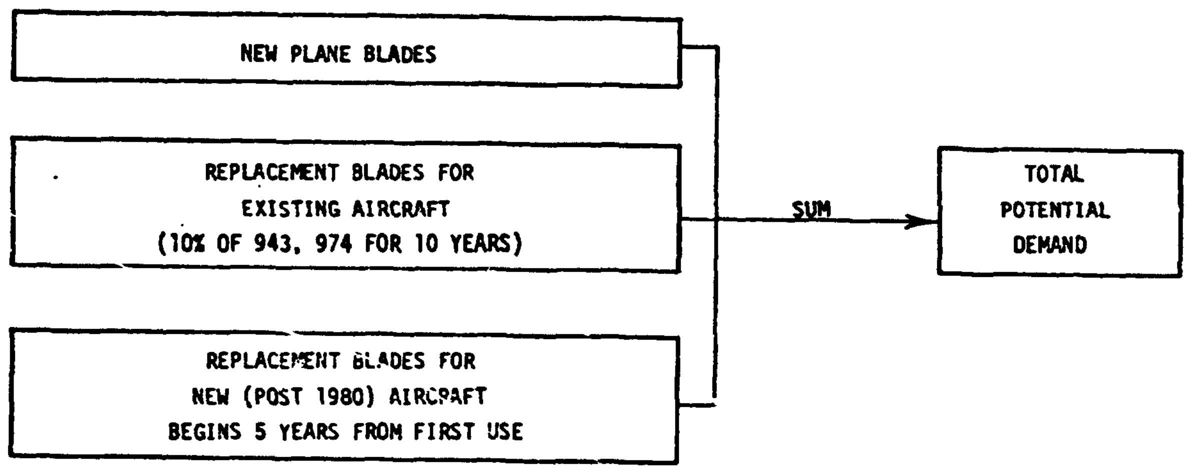

FIGURE 3-3B: ELEMENTS OF TOTAL POTENTIAL DEMAND

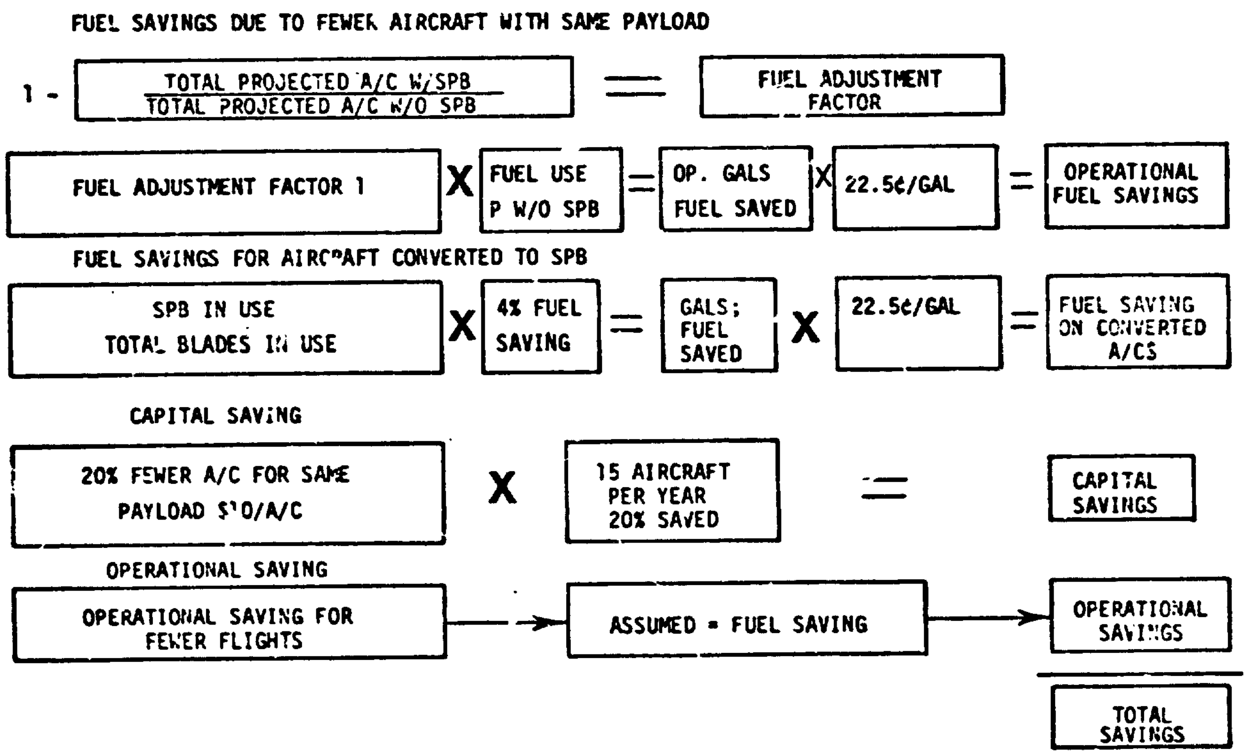

FIGURE 3-4: CALCULATION OF BENEFITS

I. TOTAL COSTS = TOTAL VARIABLE COSTS PLUS TOTAL FIXED COSTS

II. TOTAL VARIABLE COSTS

A. TRANSPORTATION COSTS - 3 ESTIMATES

1. 1½ LB. (680 GM.) PER BLADE (BEST ESTIMATE)

2. 1 LB. (454 GM.) PER BLADE (LOW ESTIMATE)

3. 2 LB. (907 GM.) PER BLADE (HIGH ESTIMATE)

B. EARTH OPERATIONS AND DIRECT MATERIAL COSTS

C. ADMINISTRATIVE OVERHEAD

III. TOTAL FIXED COSTS

A. FACTORY COSTS

1. DEVELOPMENT AND CONSTRUCTION

2. LAUNCH

B. NORMAL RETURN ON INVESTMENT

FIGURE 3-5: COSTS

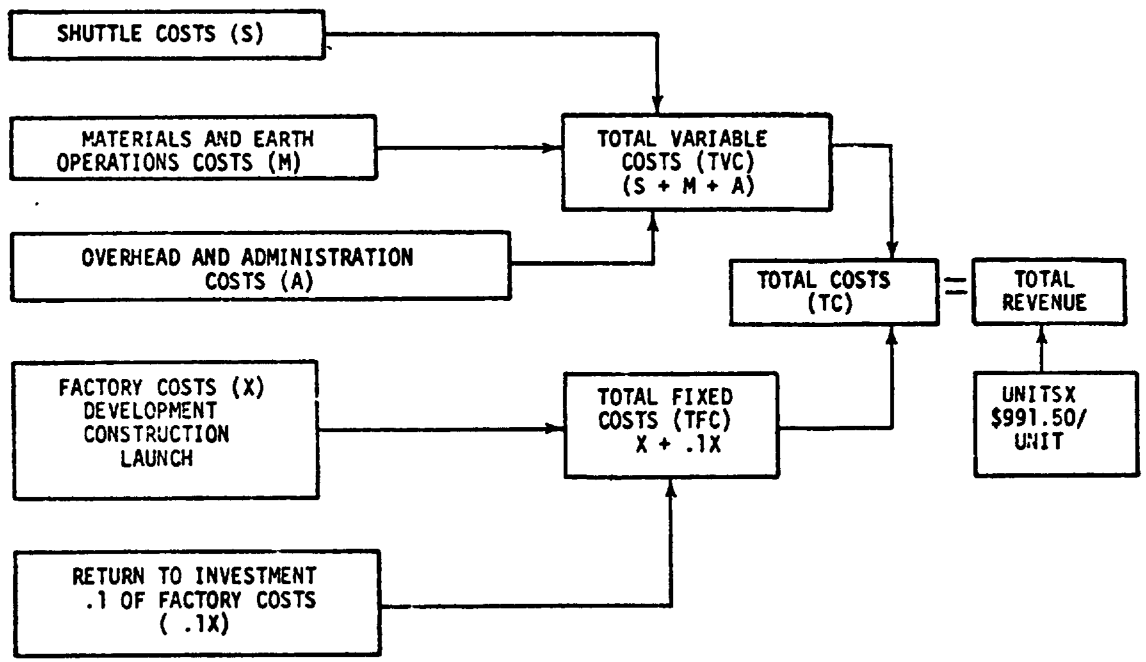

FIGURE 3-6: RESIDUAL COST ANALYSIS (10 YEAR FACTORY LIFE).
ASSUME: TOTAL COSTS (INCLUDING NORMAL RETURN) = TOTAL REVENUE

I. DEMAND WILL BE SIZABLE FROM U.S. COMMERCIAL AIRLINES ALONE - 121,987 BLADES PER YEAR MINIMUM

II. BENEFITS PER BLADE

A. $991.50 FOR REPLACEMENT BLADES

B. $21,000 FOR NEW AIRCRAFT BLADES

III. 10 YEAR (1981-1990) SAVINGS $4.381 BILLION FOR U.S. COMMERCIAL AIRLINES ALONE

IV. SUBSTANTIAL REDUCTION IN JET FUEL USAGE:

A. 6.522 BILLION GALLONS FOR 1981-1991

B. 990.4 MILLION GALLONS IN 1991 ALONE

V. SPACE FACTORY DEVELOPMENT COST ALLOWABLE - OVER $369 MILLION

VI. TURBINE BLADES A VIABLE CANDIDATE FOR SPACE PROCESSING.

FIGURE 3-7: CONCLUSIONS

3.3 Estimation of Total Potential Demand From U.S. Commercial Airlines

Table 3-1 gives actual data for U.S. commercial airlines for aircraft and turbine engines in use from 1966 to 1973 [4,5]. Utilizing these data and the forecasts of the Federal Aviation Agency, Table 3-2 was prepared which projects the total number of turbines to 1992. Estimates through 1981 were given by the FAA. The remaining estimates are linear interpolations and extensions of the FAA estimates. The linear extension is based on the last two years projected by the FAA. As such, it may be smaller than it should be since the rate of increase of aircraft falls between these two years. One additional assumption was made: For calculation of the number of potential space processed turbine blades, engines were classified as Class 80 for standard jets and Class 254 for jumbo jets. Class 80 has 80 blades that are strong candidates for space processing and Class 254 has 254. The percent of jumbo jets in service is assumed to be 21%.

Table 3-3 presents the potential space processed blades using the total number of aircraft projected. Column (1) is column 4 of Table multiplied by 80 and column (2) is column (5) of Table 3-2 multiplied by 254. This is not an adequate projection, however, because the figures do not reflect changes in aircraft numbers as a result of the advent of space processed blades. If the space processed blades provide a 20% increase in payload for new aircraft, then 20% fewer new planes will be needed to handle the projected demand.

Table 3-4 provides adjusted figures for aircraft, engines and blades, as the result of space processing of turbine blades. New aircraft needed

TABLE 3-1: AIRCRAFT DATA FOR U.S. COMMERCIAL AIRLINES

Year A/O Jan. 1	Total Aircraft	4 Engine[1] Turbine	3 Engine Turbine	2 Engine[1] Turbine	Total Turbine Engines
1966	2195	718	169	137	3608
1967	2203	799	292	300	4642
1968	2511	909	399	460	5753
1969	2463	974	528	622	6724
1970	2824	792	495	832	6317
1971	2759	817	537	837	6103
1972	2642	979	678	765	7480
1973	2583	890	759	787	7411
1974	2511	763	866	731	7112

Sources: Aero Space Facts and Figures, 1974/75 [4]
Handbook of Airline Statistics, 1971, C.A.B., Department of Transportation [6]
Aviation Forecasts, FY 1975-1986, F.A.A., Department of Transportation [3]

[1]This figure includes turboprop engines in service. Projections are based on jets only. Of 763 4-engine aircraft, 695 were jets in 1974. Of 731 2-engine aircraft, 518 were jets in 1974.

TABLE 3-2: FORECAST OF AIRCRAFT DATA FOR U.S. COMMERCIAL AIRLINES

Year	(1) Total Aircraft	(2) 4 Engine Jet Turbine	(3) 3 Engine Jet Turbine	(4) 2 Engine Jet Turbine	(5) Total Turbine Engines	(6) Turbines Class 254 (21% of Total)	(7) Turbines Class 80 (79% of Total)
1975*	2577	690	933	524	6607	1401	5206
1976*	2670	678	1032	550	6908	1451	5457
1977*	2753	670	1096	598	7164	1504	5660
1978*	2848	620	1220	644	7428	1560	5868
1979*	2931	627	1288	684	7740	1625	6115
1980*	3019	637	1370	721	8100	1701	6399
1981*	3094	644	1440	749	8394	1763	6631
1982	3169	651	1510	777	8688	1825	6863
1983	3244	653	1580	805	8982	1887	[illegible]
1984	3319	665	1650	833	9276	1949	7327
1985	3394	672	1720	861	9570	2011	7559
1986	3469	679	1790	889	9864	2073	7791
1987	3544	686	1860	917	10158	2135	8023
1988	3619	693	1930	945	10452	2197	8255
1989	3694	700	2000	973	10746	2259	8487
1990	3769	707	2070	1001	11040	2321	8719
1991	3844	714	2140	1024	11334	2383	8951
1992	3919	721	2210	1057	11628	2445	9183

Notes:
1) Total is not sum of columns due to "other" aircraft.
2) Percent of "Jumbo" Jets assumed to rise to 21% and level beyond 1976.
3) *Items are FAA Forecasts for Cols. 2-4.
4) Col. 5 is 4(Col. 2) + 3(Col. 3) + 2(Col. 4).
5) Linear projections from 1982 are low rate projections, below the average increase of previous 5 years.

TABLE 3-3: POTENTIAL SPACE PROCESSED TURBINE BLADES
(Calculated from Table 3-2) (Unadjusted)

Year	(1) Class 254	(2) Class 80	(3) Total Blades in Use
1975	355,854	416,480	752,334
1976	368,554	436,560	805,114
1977	382,016	452,800	834,816
1978	396,240	469,440	865,680
1979	412,750	489,200	901,950
1980	432,054	511,920	943,974
1981	447,802	530,480	978,282
1982	463,550	549,040	1,012,590
1983	479,298	567,600	1,046,898
1984	495,046	586,160	1,081,206
1985	510,794	604,720	1,115,514
1986	526,542	623,280	1,149,822
1987	542,290	641,840	1,184,130
1988	558,038	660,400	1,218,438
1989	573,786	678,960	1,252,746
1990	589,534	697,520	1,287,054
1991	605,282	716,080	1,321,362
1992	621,030	734,640	1,355,670

Notes: 1) Col. 1 is Col. 5, Table 3-2 times 254.
2) Col. 2 is Col. 4, Table 3-2 times 80.

TABLE 3-4: ADJUSTED PROJECTIONS OF AIRCRAFT, ENGINES, AND POTENTIAL SPACE PROCESSED BLADES REVISED FOR DECREASE DUE TO HIGHER THRUST

Year	(1) Total Aircraft	(2) 4 Engine Jet Turbine	(3) 3 Engine Jet Turbine	(4) 2 Engine Jet Turbine	(5) Total Turbine Engines	(6) Turbine[3] Engines Class 254	(7) Turbine[4] Engines Class 80	(8) Total Turbine Blades in Use[5]
1980	3019	637	1370	721	8100	1701	6399	943,974
1981	3079	643	1426	743	8336	1751	6585	971,554
1982	3139	649	1482	765	8572	1801	6771	999,134
1983	3199	655	1538	787	8808	1851	6957	1,026,714
1984	3259	661	1594	809	9044	1901	7143	1,054,294
1985	3319	667	1650	831	9280	1951	7329	1,081,874
1986	3379	673	1706	853	9516	2001	7515	1,109,454
1987	3439	679	1762	875	9752	2051	7701	1,137,034
1988	3499	685	1818	897	9988	2101	7887	1,164,614
1989	3559	691	1874	919	10224	2151	8073	1,192,194
1990	3619	697	1930	941	10460	2201	8259	1,219,774
1991	3679	703	1986	963	10696	2251	8445	1,247,354
1992	3739	709	2042	985	10932	2301	8631	1,274,934

Notes:
1) Ratio of Jumbo Jets to Conventional 21%.
2) New aircraft added each year reduced by approximately 20% due to 20% added payload.
3) Increment rounded to 50 each year.
4) Increment rounded to 186 each year.
5) Col. (8) is Col. (6) X 254 + Col. (7) X 80

per year has been reduced by 20%. The total number of turbine blades in use by commercial airlines that would also be candidates for space processing would be 943,974 in 1980, rising to 1,274,934 by 1982.

3.3.1 Potential Demand for Space Processed Turbine Blades

The demand estimates for turbine blades must take into consideration the following:

a) The Replacement of Existing Blades (Aircraft produced prior to 1980)

Consideration must be given to the rate at which existing blades could be replaced in existing aircraft. The normal rate of wearout requires a 26% replacement rate per year. At this normal wearout rate, all blades would be replaced in 3.75 years. Computation of demand based on this wearout rate produced strong fluctuations that would result in considerable over-capacity at times. Consequently, a 10 year adoption rate was chosen. This rate also exhibits flux but does so at times that could accommodate capital equipment refurbishment more readily. A 100% adoption rate was assumed on the basis that if adoption is economical for one turbine powered aircraft of commercial class, it will be economical for all commercial airliners.

b) Space Processed Blades for New Aircraft.

All new aircraft produced after 1980 are assumed to be equipped with the space processed blades.

c) Replacement Blades for Space Processed Blades.

1) Aircraft produced in 1980 and later

2) Space processed blades in aircraft produced before 1980.

This potential demand must be computed as a separate category because of the different wearout rate of the space processed blades which are assumed to have a life of 18000 hours.

The wearout time of space processed blades is assumed to average 7.5 years. The distribution of the wearout is assumed to be as shown in Figure 3-8 The distribution is:

Year	%Wearout
5	5%
6	20%
7	50%
8	20%
9	5%

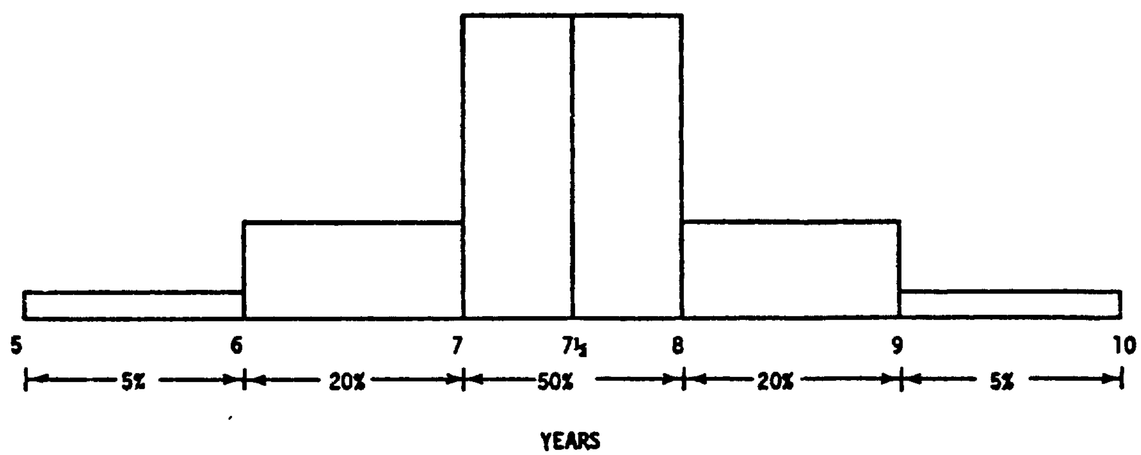

FIGURE 3-8: ASSUMED WEAROUT DISTRIBUTION OF SPACE PROCESSED TURBINE BLADES

The computation of total potential demand is shown in Tables 3-5 and 3-6. New plane blades are based on 84 new aircraft per year (Col. 1). Replacement Blades for aircraft produced prior to 1980 are shown in column (2) and terminate in 1989 when all aircraft have been converted. Prior to 1989 some earth processed blades must be replaced with earth processed blades. The replacement demand for space processed blades is calculated in Table 3-6. This table is calculated as follows: Total demand in 1980 is 121,978. Five percent of these blades will wearout in 1985, twenty percent in 1986, fifty percent in 1987, twenty percent in 1988 and five percent in 1989. These quantities must be replaced in their respective years. Thus each year replacement demand is based on total demand for 5 to 9 years previous.

Examining column (6) of Table 3-5, total potential demand for space processed blades is estimated to be 121,978 for the first five years. A surge in demand to 212,560 is expected in 1987 when large scale replacement for wornout space processed turbine blades begins. Demand falls off in 1990 to 149,558 as replacement blades for aircraft produced prior to 1980 are no longer needed. Demand is expected to rise from this year. Figure 3-9 a graphical representation of the potential demand.

Production under such a demand scheme could be handled by designing a factory capable of producing 172,800 (160,200 usable) units per year. In 1989 or 1999 a second factory could begin production to accommodate the demand and refurbishment and recapitalization of the first factory could begin if needed. Upon reopening the first factory, demand levels will have grown so that two factories would be required.

TABLE 3-5: CALCULATION OF TOTAL POTENTIAL DEMAND FOR SPACE PROCESSED BLADES

Year	(1) New Plane Blades	(2) Replacement Blades for Old Planes[1]	(3) Earth Processed Blades in Use	(4) Space Processed Blades in Use	(5) Replacements for Space Processed Blades[2]	(6) Total Potential Yearly Demand
1980	27,580	94,398	943,974	-0-	-0-	121,978
1981	27,580	94,398	849,576	121,978	-0-	121,978
1982	27,580	94,398	755,178	243,956	-0-	121,978
1983	27,580	94,398	660,780	365,934	-0-	121,978
1984	27,580	94,398	566,382	487,912	-0-	121,978
1985	27,580	94,398	471,984	609,890	6,099	128,077
1986	27,580	94,398	377,586	731,868	30,495	151,572
1987	27,580	94,398	283,188	853,846	91,483	212,560
1988	27,580	94,398	188,790	975,824	115,879	236,956
1989	27,580	94,392	94,392	1,097,802	121,978	243,055
1990	27,580	-0-	-0-	1,219,768	122,283	149,558
1991	27,580	-0-	-0-	1,247,348	124,650	152,230
1992	27,580	-0-	-0-	1,274,928	135,447	163,027
1993	27,580	-0-	-0-	1,302,505	161,660	186,240

Notes: 1) Ten year adoption rate to 100% adoption (10% of original total per year).
2) Calculated in Table 6.
3) Sum of Cols. 1, 2, and 5. Note that this total is for U.S. Commercial Airlines only.

TABLE 3-6: CALCULATION OF REPLACEMENT DEMAND FOR SPACE PROCESSED BLADES
(Wearout Year (t + x) (End of Year Total)

Year	(1) Total Potential Demand	(2) t + 5	(3) t + 6	(4) t + 7	(5) t + 8	(6) t + 9	(7) Replacement Total
1980	121,978						
1981	121,978						
1982	121,978						
1983	121,978						
1984	121,978						
1985	128,077	6,099					6,099
1986	151,572	6,099	24,396				30,495
1987	212,560	6,099	24,396	60,988			91,483
1988	236,956	6,099	24,396	60,988	24,396		115,879
1989	243,055	6,099	24,396	60,988	24,396	6,099	121,978
1990	149,558	6,404	24,396	60,988	24,396	6,099	122,283
1991	152,230	7,579	25,615	60,988	24,396	6,099	124,650
1992	163,027	10,628	30,314	64,037	24,396	6,099	135,447
1993	186,240	11,848	42,512	75,586	25,615	6,099	161,660
			47,390	106,280	30,314	6,404	
				118,476	42,512	7,579	
					47,390	10,628	
						11,848	

Notes: 1) Col. (t + 5) is 5% of Total Potential Demand 5 years previous.
Col. (t + 6) is 20% of Total Potential Demand 6 years previous.
Col. (t + 7) is 50% of Total Potential Demand 7 years previous.
Col. (t + 8) is 20% of Total Potential Demand 8 years previous.
Col. (t + 9) is 5% of Total Potential Demand 9 years previous.
2) Total Potential Demand is Col. 1, Table 3-5 plus Col. 2, Table 3-5 plus Replacement Total, Col. 7 above.

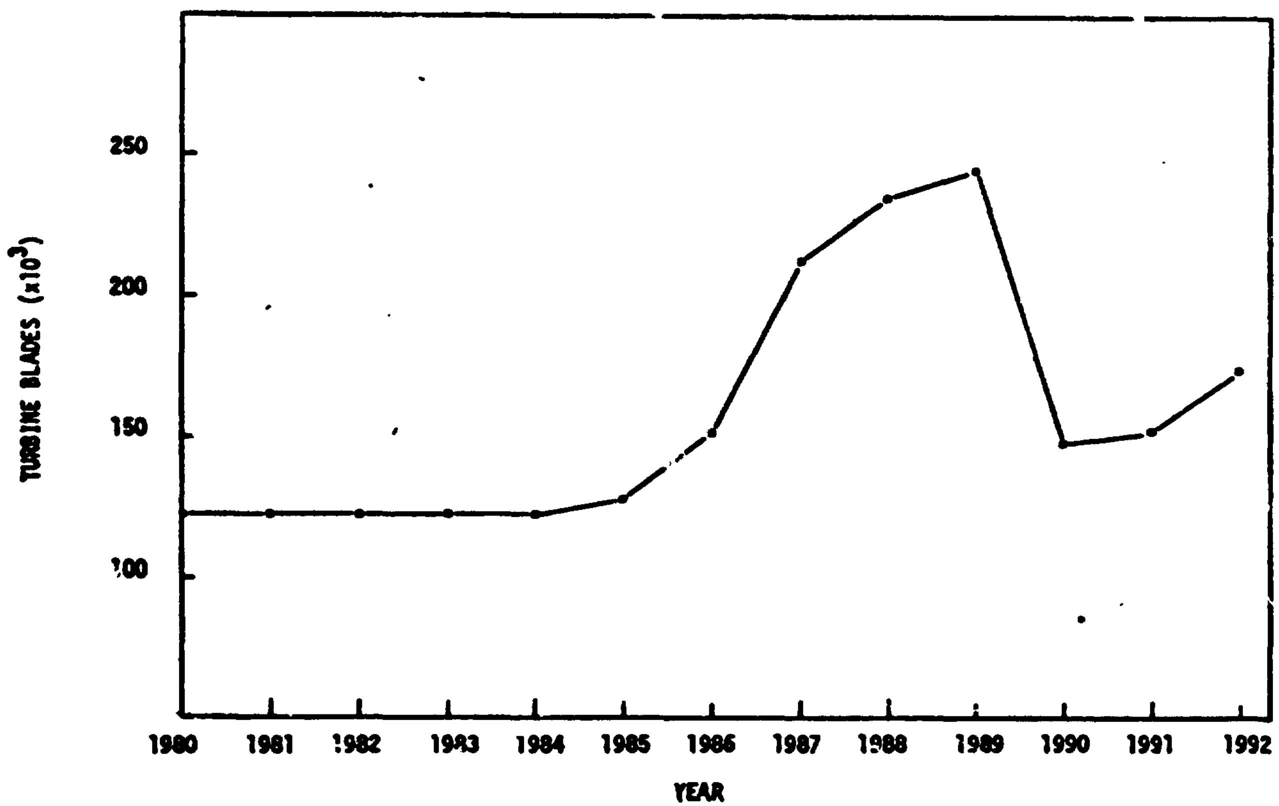

FIGURE 3-9: TOTAL POTENTIAL DEMAND FOR SPACE PROCESSED TURBINE BLADES

3.4 Benefits of Space Processed Turbine Blades

3.4.1 Introduction

The benefits of space processed turbine blade derive from their anticipated technological superiority over earth processed blades. The benefits calculated herein are based on the following critical assumption regarding the performance of turbine engines utilizing space processed blades:

a) For blades installed in existing engines, blades will double their life expectancy from 9000 to 18000 hours and achieve a 4% reduction in fuel use. Altern[illegible], increased thrust could have been calculated as a benefit. This was not done since costly modification of existing aircraft might be involved to allow increased payload capacity for passengers. The possibility exists that modification would be an economical choice. This option was not calculated, however.

b) For blades installed in new aircraft a 10% increase in thrust (no fuel saving) was assumed. A 10% increase in thrust was then assumed to give a 20% increase in payload potential. This is a conservative estimate. One estimate has related a 11.6% increase in thrust to a 40% increase in payload [1, p.4].

The calculation of benefits is limited to the benefits accruing to the buyer of the turbine blades. Since the buyer must, in the absence of subsidy, be willing to pay the full costs of production, his benefits must be at least of equal value. The full costs of production must include a normal return to the manufacturer for his services. No subsidy is assumed in the manufacturing operation. Benefits calculated are of two types: a) fuel savings and b) capital savings with associated operational savings.

3.4.2 Calculation of Fuel Savings

Table 3-7 shows jet fuel consumption and projected consumption for the period 1966-1992. The FAA projects only fuel consumption of domestic flights of U.S. Commercial Airlines. These are flights that originate and terminate within the U.S. Non-domestic flight fuel consumption is estimated as 20% of the total fuel consumption. This figure is slightly below the historical average but the recent trend has been downward. The figures of Table 3-7 are projections based on current trends.

The figures do not reflect fuel consumption adjustments that must be made to account for space processing of blades. Two adjustments must be made: 1) an adjustment for the reduced number of new aircraft as a result of the increased thrust and b) an adjustment for fuel savings due to better fuel economy in pre-1980 aircraft. These computations are shown in Table 3-8 and 3-9.

Table 3-8 shows the aircraft needed without the increased thrust of space processed blades (Column (1)) as opposed to the aircraft needed with production of space processed blades (Column (2)). The ratio of Column (2) to Column (1) subtracted from 100% gives the percent fuel savings anticipated by year (Column (3)) because of fewer aircraft needed to carry the same payloads. Column (3) times the original fuel projection yields fuel savings in gallons (Column 4) as the result of reduced operational levels. Subtracting Column (4) from Column (1) of Table 3-6 yields the adjusted fuel use figures (Column (5)). The dollar saving per year is estimated by multiplying the gallons saved (Column 4) times the jet fuel price [7] of 22.5 cents per gallon (2) yielding Column (6). The operational fuel savings so calculated rise from $25 million in 1981 to $223 million in 1992.

Table 3-9 calculates the fuel savings as existing (as of 1980) aircraft are converted to space processed blades. The adjustment is made on the basis

TABLE 3-7: JET FUEL CONSUMPTION AND PROJECTED CONSUMPTION (Air Carrier Only)

Year	(1) Millions of Gallons (000,000) Total Jet Fuel Consumption	(2) Millions of Gallons (000,000) Domestic Flight Jet Fuel Consumption	(3)[1] Non-Domestic Jet Fuel Consumption
1966	5,821	3,907	1,914
1967	6,440	4,568	1,872
1968	8,400	6,043	2,357
1969	9,041	7,063	1,978
1970	10,174	7,826	2,348
1971	10,460	7,985	2,475
1972	9,919	7,935	1,984
1973	10,648	8,518	2,130
1974	10,293	8,234	2,059
1975	10,869	8,695*	2,174
1976	11,456	9,165	2,291
1977	12,449	9,959	2,490
1978	12,703	10,162	2,541
1979	13,261	10,609	2,652
1980	13,791	11,033	2,758
1981	14,344	11,475	2,869
1982	14,897	11,917	2,980
1983	15,449	12,359	3,090
1984	16,002	12,801	3,201
1985	6,554	13,243	3,311
1986	17,107	13,685	3,422
1987	17,659	14,127	3,532
1988	18,212	14,569	3,643
1989	18,76[illegible]	15,011	3,753
1990	19,317	1[illegible],453	3,864
1991	19,869	15,895	3,974
1992	20,422	16,337	4,085

Notes: 1) Estimated (Based on Ratio of Domestic to Non-Domestic Passenger Miles). Assumed to be 20% of total after 1971 (25% of Domestic).
2) *Items are from FAA Aviation Forcasts [3].

TABLE 3-8: COMPUTATION OF FUEL ADJUSTMENT FOR REDUCED AIRPLANE NUMBERS DUE TO INCREASED THRUST OF NEWLY PRODUCED AIRPLANES

Year	(1) Total Aircraft Projected when Space Processed Blades not produced	(2) Total Aircraft Projected when Space Processed Blades are produced	(3) Fuel 1 Adjustment Factor (% Fuel Savings)	(4) Operational Fuel Saving2 (Gals) (000,000)	(5) Fuel Use Projection After 1st Adjustment	(6) Operational Fuel Saving Nearest $Million
1980	3019	3019	0	0	13791	0
1981	3094	3069	.81	111.7	14232.3	25
1982	3169	3129	1.27	189.2	14707.8	43
1983	3244	3189	1.70	262.6	15186.4	59
1984	3319	3249	2.21	353.6	15648.4	80
1985	3394	3309	2.50	413.9	16140.1	93
1986	3469	3369	2.98	509.8	16591.2	115
1987	3544	3429	3.24	572.2	17086.8	129
1988	3619	3489	3.60	655.6	17556.4	148
1989	3694	3549	3.93	737.4	18026.6	166
1990	3769	3609	4.25	821.0	18496.0	185
1991	3844	3669	4.55	904.0	18965.0	203
1992	3919	3729	4.85	990.5	19431.5	223

Notes:
1) (3) is 100% minus (2)/(1).
2) (4) is (3) times (1) of Table 3-7.
3) (5) is (1) of Table 3-7 minus (5).
4) (6) is (4) times 22.5 cents/gallon.

TABLE 3-9: COMPUTATION OF FUEL SAVINGS FOR CONVERSION OF EXISTING AIRCRAFT TO SPACE PROCESSED TURBINE BLADES

Year	(1) Space Processed Blades in Use in Pre 1980 Aircraft	(2) Total Blades in Use	(3) Ratio[2] (1)/(2)	(4) Fuel Adjustment Factor ((3) x .04)	(5) Fuel Saving on Converted Aircraft (Mil Gals)	(6) $ Fuel Savings on Converted Aircraft (Mil $)
1980	0	943,974	0	0	0	12.49
1981	94,398	971,554	9.71%	.39%	55.51	12.49
1982	188,796	999,134	18.89%	.76%	111.78	25.15
1983	283,104	1,026,714	27.57%	1.10%	167.05	37.59
1984	377,592	1,054,294	35.81%	1.43%	223.77	50.35
1985	471,990	1,081,874	43.62%	1.74%	280.84	63.19
1986	566,388	1,109,454	51.05%	2.04%	338.46	76.15
1987	660,768	1,137,034	58.11%	2.32%	396.41	89.19
1988	755,184	1,164,614	64.84%	2.59%	454.71	102.31
1989	849,582	1,192,194	71.26%	2.85%	513.76	115.60
1990	943,974	1,219,768	77.38%	3.10%	573.38	129.01
1991	943,974	1,247,348	75.67%	3.03%	574.64	129.29
1992	943,974	1,302,505	72.47%	2.90%	563.51	126.79

Notes: 1) (2) is Col. (3) Table 3-5 plus Col. (4) of Table 3-5.

2) This ratio is the ratio of (1) space processed blades in use in aircraft produced prior to 1980 to (2) the total number of blades in use of all types in all planes. This eliminates post 1980 aircraft from the fuel saving since their benefits are taken up in increased thrust and payload. When multiplied by 4% fuel saving it yields fuel adjustment factor (4).

that aircraft converted will use 4% less fuel. The fuel adjustment factor (Column (3)) thus is the product of the ratio of space processed blades in use in pre-1980 aircraft (Column (1)) to the total blades in use (Column (2)) times 4%. Fuel adjustment factor 2 multiplied by the fuel use after the first adjustment (Column 5, Table3-8) yeilds the fuel saving on converted aircraft (Column (5)). The use of only the blades in pre-1980 aircraft means that no added advantages have been attributed to post 1980 aircraft other than those computed below. Multiplying Column (5) by 22.5 cents a gallon yields Column (6), the fuel saving on aircraft converted to space processed turbine blades. In dollars this represents a savings of $12.49 million in 1980 and rising to $129.29 million in 1991.[1]

3.4.3 Capital Savings

Although existing aircraft might not be able to take full payload advantage of the 10% additional thrust, new aircraft would be designed to do so. Estimates of the increased payload range from a highly conservative 10% to 40%. For estimating purposes, the assumption will be made that all aircraft produced after 1980 with the space processed turbine blades will have an increased payload of 20%. The number of aircraft purchased can then be reduced by one-fifth, and the capital saving estimated. The average cost of an aircraft is assumed to be ten million dollars for purposes of computation. This is a rough average price for the entire spectra of commercial aircraft purchased. This figure is an estimate based on the following considerations. First, the average value of aircraft purchased

---

[1]The fuel adjustment factor begins to decline in percentage terms in 1990 because the weightingof aircraft produced after 1980 continues to grow while all pre-1980 aircraft are fully converted.

from U.S. manufacturers in 1973 was $12.65 million, but 42% of these were "jumbo" jets which pushed the average up. Secondly, new orders for jumbo jets relative to more standard size jets has decreased in 1974 [4]. Thirdly, the ratio of jumbo to standard orders is assumed to be in the range of 20% to 25% of future orders. This would make the $10 million dollar (1974 dollars) per plane estimate a reasonable figure.

Using the data from Table 3-1, 75 new aircraft were projected for each year. A decrease of 20% would reduce production by 15 to 60 per year. The yearly capital savings would be

15 x $10 million = $150 Million/Year

For a 12 y :r period this would be a total saving of $1800 million.

3.4.4 Total Benefits

Total Benefits are given in Table 3-10. Capital savings of 210 million per year are shown in Column (1). Fuel saving from converted aircraft is shown in Column (2). An added benefit not computed previously is the savings accruing to the airlines as a result of a reduced operating level. With 20% added payload there would be a reduced fuel consumption from fewer flights. The fewer flights would also result in a reduction in other operational expenses such as personnel, e.g. less pilots, service personnel. Much of the operational expense might not be reduced however since it would depend on the numbers of passengers, e.g., the number of stewardesses. For computational purposes the non-fuel operational saving of a reduced number of aircraft is estimated to be equal to the operational fuel savings calculated in Table 3-8, Column (6). The total operational savings would then be double the amount in Table 3-8, Column (6). This figure is shown in Column (3). The total savings are given in Column (4). Total yearly savings are thus estimated to be 210 million in 1980 and rise to 783 million in 1991. The total 13 year period saving (1980-1991) would be 6618 billion dollars.

3.4.5 Benefits per Blade

The nature of benefits, and thus the value per blade, differs for new aircraft produced with 20% added payload and existing aircraft. The value per blade per year of existing aircraft can be estimated by dividing the fuel savings for the year 1981 by the number of blades in use on pre-1980 aircraft (\$12.48 million ÷ 94,398). This is \$132.20 per year. For a 7.5 year life the per blade value is \$991.50.

For new aircraft, every 4 blades produced in space provides enough thrust for 5 earth produced blades. Every four aircraft produced with space

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TABLE 3-10: TOTAL POTENTIAL BENEFIT PER YEAR OF SPACE PROCESSED TURBINE BLADES

Year	(1) Capital Saving $(000,000)	(2) Fuel Saving on Converted Aircraft (Nearest $Million)	(3) Saving from Reduced Operational Level	(4) Total Saving Per Year (Nearest $Million)
1980	210	0	0	210
1981	210	12	50	272
1982	210	25	86	321
1983	210	38	118	366
1984	210	50	160	420
1985	210	63	186	459
1966	210	76	230	510
1987	210	89	258	557
1988	210	102	296	608
1989	210	116	332	658
1990	210	129	370	709
1991	210	129	406	745
1992	210	127	446	783

processed blades has the payload potential of five aircraft with earth provened blades. Thus an airline company can save the cost on one plane ($10 million) in every five. The value of the 27,580 new plane blades produced in one year is the $210 million initial capital savings plus the yearly operational savings of 50 million times the life expectancy of 7 1/2 years.[2] This figure is taken from the 1981 figure for Column 3, Table 10. Since the total number of new blades in use is only 27,580 what was produced in 1980, the previous year, the entire capital saving, and operational saving is from those blades. But future operational savings will also continue for 7 1/2 years on the average.

$210 million + $375 million = $585 million saving for 27580 blades.

The per blade benefit is thus:

$$\frac{\$585 \text{ million}}{27580} = 21{,}211.02$$

This figure is rounded to $21,000

[2]If the capital saving were only 1/2 these calculations and there were no operational savings, the value would still be high at $3807 per blade.

3.5 Costs Analysis

3.5.1 Delineation of Costs

The cost of producing space processed blades will include the following costs:

a. Transportation Costs of materials to the space factory and finished product to earth. (Also referred to as Shuttle Costs)

b. Factory Costs per unit. These include:

   1. Development Costs of the Factory
   2. Launch Costs of the Factory
   3. Operation and Material Costs of the Factory (Direct Costs)

c. Administrative Overhead of the contracting firm.

d. A Normal Return to the contracting firm.

a) Derivation of Transportation costs of the materials and finished product is based on the costs derived for the space shuttle in Chapter 2.0 of this report. Assuming 37 total flights per year for a 12 year period the per pound cost would be $326. This is the figure that will be utilized. Note that not all of the flights are space processing flights. However, the learning experience of these flights results in a lower cost of operation to all users.

b) The development of factory cost estimates at this point in time involves the formulation of a critical set of assumptions. The space factory costs for turbine blades must include the costs of design and development of automated machinery and furnaces capable of producing blades at a rate of over 100 thousand a year. An accurate estimate would involve a sizable engineering study. Some guidelines involving sizes, outputs, and power requirements are given in Chapter 4.0 of this report.

As an alternative to directly developing costs of the space factory, this cost will be treated as a residual value. That is, all other costs and revenue will be placed together in appropriate equation form with factory costs as an unknown. Solving the equation will yield a factory cost figure which is the maximum the market will bear.

c) Administrative Overhead of the contracting firm will be assumed to be 50% of all production costs.

d) The normal return will be assumed to be 10%.

3.5.2 Residual Cost Analysis

This section of the study assumes that a price for space processed turbine blades is set and finds the maximum cost of the space factory at which the firm would still be able to achieve an acceptable rate of return. Based on the demand and benefit analysis, this residual cost figure says in essence, "If the factory can be put into service for this cost, then the operation will be profitable at an acceptable rate of return."

Let X = Factory Cost

Thus .1X = Return on Investment

We proceed from the assumption that total costs (TC) must equal (TR) where the return to the producer is treated as a cost of production.[3]

The total costs of production are broken into:

A. Fixed Costs (FC) (Development, Construction and Launch)
X = Factory Costs
.1X = Return on Factory Cost Outlay

[3] The economic nomenclature for this return is called a normal profit. It is customarily treated as a cost of production because unless it is forthcoming, producers will not produce the product, rather seeking more favorable production lines.

B. Variable Costs (VC)
S = Shuttle Costs @ $326/lb.
M = Material Costs and Operational Costs
A = Administrative Costs

3.5.3 Calculation of Costs

3.5.3.1 Shuttle Costs

The pounds of weight in materials and finished blades includes:

(1) Mold weight
(2) Materials for blade weight
(3) Storage rack weight

These weights will have the strongest bearing on differences in the costs of operation. Three estimates will be given: (1) a high of 2 lbs. (907.2 gm.) per blade, (2) a low of 1 lb. (453.6 gm.), and (3) a best estimate of 1 1/2 lb. (680.4 gm.)

Shuttle Costs - Best Estimate

172,800 Production Units X 1.5 lb./blade = 259,200 lb. per year

At $326 per pound this is: $489 per blade

S = 172,800 X $489 = $84,499,200 for one year

10S = $844,992,000 for 10 years

Shuttle Costs - High Estimate

172,800 Units X 2 lb./blade = 345,600 lb. per year

At $326 per pound this is:

S = 345,600 X $326 = $112,665,200 for one year

10S = $1,126,652,000 for 10 years

Shuttle Costs - Low Estimate

172,800 Units X 1 lb./blade = 172,800 lb. per year.

At $326 per pound this is:

S = 172,800 X $326 = $56,332,800 for one year

10S = $563,328,000 for 10 years

3.5.3.2 Material and Operational Costs

The current price of earth processed blades is approximately \$130 per blade. Assuming that most finishing operations re conducted on earth and that materials will be higher, we assume this price to be the cost of earth operations and materials.

M = 172,800 Units X \$130 per unit = \$22,464,000 for one year or

\$224,640,000 for 10 years

3.5.3.3 Overhead and Administrative Costs

These costs tend to vary by the type of operation conducted and t efficiency of the firm. For many firms a reasonable figure would be 50% of the other variable costs of the operation. However, because of the nature of the variable costs associated with outer space manufacturing, notably the shuttle costs, such an estimate would appear to be too high. A more reasonable estimate would be to take the \$130 price of earth processed blades and assume that about 25% of the price is due to overhead and administrative costs. Reflecting that outer space manufacturing will involve added handling and coordination activities, it would be reasonable to double that figure per unit. Thus we estimate that:

50% X \$130 = \$65/unit is a reasonable estimate of these costs.

A = \$65 X 172,800 Units = \$11,232,000 per year

or

10A = \$112,320,000 for 10 years

Thus from the standpoint of the contractor total variable costs, using the best estimate of Shuttle Costs,

TVC = S + M + A

= 84,499,200 + 22,464,000 + 11,232,000

= \$118,195,200

per year or \$1,181,952,000 for a 10 year factory life period.

Assuming the price of the turbine blades to be $991.50 (equal to the lower benefit computed for replacement blades), with a 10 year factory life producing 160,200 usable units per year, the total revenue from sale of the blades would be:

160,200 Units X $991.50 = $158,838,300

per year of 1,588,383,000 for 10 years. The <u>minimal</u> conditions for production is that total revenue (TR) equals total cost (TC). Thus we can substitute TR for TC and then solve for X, factory costs.

We have:

$$TC = TVC + X + .1X$$

and $TR = TC$

thus $TR = TVC + X + .1X$

Substituting dollar figures for 10 years yields:

$$\$1{,}588{,}383{,}000 = \$1{,}181{,}952{,}000 + X + .1X$$

solving for X

$$X = \frac{\$1{,}588{,}383{,}000 - 1{,}181{,}952{,}000}{1.1}$$

$$= \frac{\$406{,}431{,}000}{1.1}$$

$$= \$369{,}482{,}727$$

Thus factory costs of design, constructing and launching could not exceed the above amount, over three hundred fifty million dollars.

C-2

3.5.4 Alternative Calculations

a) Assuming that the total weight of mold, materials, and storage racks is 2 lbs. (907.2 gms.) per blade, the residual cost analysis would be as follows:

S = \$112,665,200 for 1 year

TVC = (S + M + A) for 1 year

= \$112,665,200 + \$22,464,000 + \$11,232,000

= \$146,361,200

TC = 1.1X + \$1,463,612,000 for 10 years

TR = \$1,588,383,000 for 10 years

Setting TC = TR

\$1,588,383,000 = 1.1X + \$1,463,612,000

1.1X = \$124,771,000

X = \$113,428,182

This figure is much smaller than the best estimate figure and probably would put the economic feasibility of the manufacturing program in doubt, if the price of the blades was set at \$991.50 each. However, the extremely high value of the space processed blade for newly produced aircraft (almost \$22,000 per blade) poses the possibility of production for this one area even if space processed blades were not economical for replacement in existing aircraft. With demand from this source anticipated at or above 27,580 blades a year, a much smaller factory concept involving production at 30,000 units per year, or 2500 units per month, may well be feasible.

Another possibility is that the producer could engage in price discrimination somewhat, placing a lower than cost subsidized price on blades for existing aircraft and a higher than cost price on blades for new aircraft. This would potentially allow a reasonable return on the investment. Because of the extremely high value calculated for these new blades, savings to the airlines that were passed on by pricing blades below their total benefit, would encourage a faster writeoff and replacement of existing aircraft. Thus the lower priced the producer makes the blades for new aircraft, the more likely the potential quantities demanded are to respond by shifting into new aircraft.

b) Assuming that the total weight of mold, materials, and storage racks is only 1 lb. (453.6 gms.) per blade, the residual cost analysis would be as follows:

S = \$56,332,800 for 1 year

TVC = S + M + A for 1 year

= \$56,332,800 + \$22,464,000 + 11,232,000

= \$90,028,800

TC = 1.1X + \$900,288,000 for 10 years

TR = \$1,588,383,000 for 10 years

Setting TC = TR

\$1,588,383,000 = 1.1X + \$900,288,000

1.1X = \$1,588,383,000 - \$900,288,000

1.1X = \$688,095,000

X = \$625,540,909

Under this calculation the costs of designing constructing and launching the space factory could not exceed the above figure, in excess of six hundred million dollars.

3.5.5 Another Possible Alternative

This study has been designed estimating costs on the assumption that the turbine blade would be pre-cast on earth and transported to the space factory in a mold. This alternative adds considerably to the transport costs since the mold weight reduces the effective payload of the shuttle. As an alternative to using this procedure, the following approach bears further consideration.

Instead of carrying the mold along, the space factory could be equipped with permanent molds that could be replaced on an as needed basis. This substantial reduction in weight transported to and from the space factory would considerably lower transport costs, but would alter the costs structure in other ways. More time and effort would be necessary to re-set the pre-cut blades in their molds and to remove them once they have been recast. This operation may dictate that the space factory be manned on a full time basis.

Manning the space factory may have some further advantages in that a less automated, simpler design system could be used for production, lowering costs of design and production of the capital equipment. Increased costs would be incurred by a requirement that living quarters be provided in the space factory for the worker or workers. The provision of living quarters, however, does not require additional technological development.

The costs saving from a reduction of the transport weight from 1 1/2 lbs. (best estimate with mold) to 1 lb. is:

1/2 ($326 1 lb.) = $163 per blade

$163 X 14400 = $2,347,200/month

$163 X 172,800 = $28,166,400/year

$163 X 1,728,800 = $281,664,000/10 year life of factory

Consequently, if these savings, along with other design and capital equipment savings are greater than the cost of providing living quarters for workers, the manned approach would be more economical.

The manpower costs themselves would probably be only a very small proportion of this total. For example, 2 men paid at a rate of $50,000 each per year would be only $1.2 million for 10 years. There would be some added manpower costs for training and standby personnel (assuming 30 day tours in space), but total costs should not exceed $2.5 million to $3 million.

Table 3-11 shows the marginal savings for transport costs by pounds and grams on a per blade, per month, and per year basis.

TABLE 3-11: SAVINGS ON TRANSPORT COSTS FROM WEIGHT REDUCTIONS

	Savings		
Reduce Weight By	Per Blade	Per Mo.	Per Yr.
1 pound (453.6 gm.)	$326	$4,694,400	$56,332,800
1/2 pound (226.8 gm.)	$163	$2,347,200	$28,166,400
1/4 pound (113.4 gm.)	$ 81.50	$1,173,600	$14,083,200
100 gm.	$ 71.86	$1.034,784	$12,417,408
250 gm.	$179.65	$2,586,960	$31,043,520
400 gm.	$287.44	$4,139,136	$49,669,632

3.5.6 Qualifications to the Study

The foregoing study is subject to several qualifying remarks. These remarks are designed to cover some contingent situations that might arise.

3.5.6.1 Importance of Technological Assumptions

The technological assumptions are critical to the resultant values in the study. The values react to any change in the technological assumptions. The framework of the study is outlined in a fashion that would allow recomputation for any set of technological guidelines in a relatively short time period. From the standpoint of benefits calculated, the primary assumption is the reduced fuel usage. For new plane blades, the benefits lie heavily upon capital savings, but the study's conclusions are based on replacement blade benefits, which are considerably lower. Consequently, all of the capital savings could be removed from the study and the new plane blades would still have a value of $13,596 per blade. For the new plane blades in particular, the technological assumptions could be relaxed considerably. Replacement blades do not enjoy this luxury.

3.5.6.2 Potential Changes in Aircraft Design and Operation

A significant reduction in the fuel consumption projections for the coming two decades could result in a reduction of the projected benefits and affect the viability of space production. With the recent energy crisis considerable effort has been devoted in the direction of reduced fuel consumption. Fuel savings could result from improvements in both aircraft design and operations, on the ground as well as in the air. An example of this is a 4% fuel saving by Pan-Ambetween July and October 1973. These economies were realized by decreased cruise speeds, optimum flight profiles and better ground maneuvers. Estimates of potential fuel reduction are as high as 75% [5, pp. 26-43].

A study conducted by the American Institute of Aeronautics and Astronautics has tabled potential fuel savings from structural improvements of aircraft [2, p. 19]. Among the areas of improvement potential cited for propulsion technological development are "improved materials for the hot end of the compressor; more efficient cooling schemes and improved materials for the turbine;" [8, p. 31].

This study operated under the assumption that fuel consumption would follow the pattern projected by the FAA in their Aviation Forcasts [3]. A significant reduction in the projected fuel consumption levels from the 1971 projections to the 1975 projections was noted. Much of this reduced projection may reflect anticipated improvements in aircraft technology and operation. If so, then the technological changes will not affect the results of the study as strongly. However, further reductions of fuel consumptions would further reduce benefits.

Another technological problem that may or may not enter into consideration is the potential development of other types of engines, such as a hydrogen powered engine. Because of the chemical characteristics of hydrogen as a fuel, the use of space processing would have to be reevaluated. The use of hydrogen powered technology is not expected before 1990 to 2000, however, and would not necessarily interfere with potential space production of blades prior to that time. Other types of fuels and power plants would have to be evaluated on their own merits.

3.5.6.3 Earth Developments in Technology

This study was predicated on the existing level of earth technology for production on earth. It may be that considerable advances in earth technologies over the next decade or two might reduce the differential in performance between blades produced on earth versus blades produced in space. On the other hand, it is possible that improved technologies developed on earth may still be improved by space manufacturing. Developments along this line were not considered for purposes of the study.

3.6 References

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6. ______________ Handbook of Airline Statistics.

7. Aviation Week, June 1974.

8. American Institute of Aeronautics and Astronautics, Aircraft Fuel Conservation, June 30, 1974.

Other References in this area which may provide useful data are:

Chung, A. M., and C. S. Yan, "An Econometric Analysis of Potential Benefits to the U.S. Economy from Metallurgical Improvements in Space-Processed Monocrystal Turbine Blades," NAS-8-28179 Contract Report, 1972.

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4. TURBINE BLADE PROCESSING

4.1 Summary

Space processing of directionally solidified eutectic-alloy type turbine blades is envisioned as a simple remelt operation in which a pre-cast blade or blades are remelted in a pre-formed mold. Containerless melting does not seem to be feasible at this time because of the surface tension involved of the molten metal, the complex blade shape, and the necessary dimensional control. The weight of the large number of blades (172,800) which must be produced annually, the weight of the necessary associated processing facilities, and the long process time eliminates the shuttle as a possible space factory for turbine blades. Therefore, a permanent space factory is required using the shuttle only as a means for maintenance and refurbishment.

With a shuttle cargo load of 32,000 lb. and a maximum allowable weight of blades, molds, and storage facilities as 2 lb. per blade at least eleven shuttle trips per year are required. For a margin of safety, monthly shuttle trips have been assumed. On a monthly or 30 day basis, 14,400 blades are to be manufactured giving a shuttle cargo of 28,800 lb. per trip. In each 30 day period, the blades should be produced in approximately 25 days to leave sufficient time for maintenance and refurbishment of the permanent space factory.

Three different process systems based on (a) induction melting, (b) continuous resistance furnaces, and (c) batch resistance furnaces were evaluated. Table 4-1 summarizes the main points in each system. Induction melting techniques do not seem to be applicable to space

processing of turbine blades. Even at fast solidification rates, too many induction units would be required for one coil per unit. In most cases, induction melting units are large and the space necessary to house all of the units plus the associated storage and handling equipment would be excessive. The number of units could be reduced by utilizing multi-coil units but, in any event, the total power required for induction melting of turbine blades is probably too great for space processing. Also, the number of blade-mold combinations (one blade per mold) which must be crew-handled during refurbishment is staggering.

Resistance type furnaces either continuous or batch hold the best possibilities for space processing. The solidification rate in either case must be high, on the order of 7 in/hr, to maintain a reasonable number (8) of furnace systems. Regardless, whether a continuous or batch system is used, a multi-blade mold must be developed because, even with high solidification rates, single blade molds will require too many furnaces. In either process, the size of the furnaces required is much less than the size of the associated facilities for storage and handling. Consequently, the size of the latter is of major consideration in determining the size of the space factory required. The materials storage and handling systems for the continuous systems will occupy about twice the volume as the batch process. Also, the materials handling equipment for the continuous process likely will be more complex than for the batch process. The power requirements for each process border on being reasonable but new methods of obtaining electrical power should be investigated. The use of removeable mold storage compartments decreases the number of blade-mold units which need be handled during refurbishment. In considering all aspects, a batch resistance furnace type process using a multi-blade mold seems to offer the best possibility for turbine blade processing.

New technological advances must be made in order to minimize the number of furnaces required and, thus, decrease to a reasonable amount the associated materials storage and handling equipment. These advances must be mainly in the areas of mold materials and design, furnace design, and the determination of the fastest possible solidification rate to obtain the desired alloy properties. All aspects of design for all the different associated equipment necessary for production are dependent on solidification rate (rate of production) and the number of blades which can be processed per mold. These determine the number and size of the furnaces, size of the materials storage facility, the space requirements to house the entire system and the total power requirements.

Any of the processes outlined will depend on obtaining high solidification rates and blade-mold compatibility. The dimensional tolerances of the blade depend on the compatibility between the mold and the blade prior to and during the entire process. Technologically, this may be the greatest handicap to overcome. At the present time, it is felt that the technology required for construction of the basic furnaces, the materials storage facilities, and the materials handling equipment is available. The question remains, if the high solidification rates required to reduce the number of furnace systems is feasible to obtain the alloy properties necessary and whether a mold material can be found that will be satisfactorily compatible to the process.

TABLE 4-1: SUMMARY OF TURBINE BLADE PROCESSING

	Induction Melting			Resistance		
				Continuous	Batch	
	7.1 in/hr .05 mm/sec	.71 in/hr .005 mm/sec	.496 in/hr .0035 mm/sec	7.1 in/hr .05 mm/sec	7.1 in/hr .05 mm/sec	0.5 in/hr .00353 mm/sec
Is mold needed	yes	yes	yes	yes	yes	yes
Blades per mold	1	1	1	3	6	6
Time to produce each blade	36.67 m	366.7 m	523.3 m	3.42-8.55 h	.61 h	8.66 h
Time interval between molds	1.33 m	1.3 m	1.3 m	1 h	1.39 h	1.34 h
Total time to produce each blade	38.0 m	368 m	524.6 m	3.42-8.55 h	2 h	10 h
No. of furnaces (or coils) to produce 14,400 blades/mo	16	150	215	8	8	8
No. of chambers or coils per furnace	1	1	1	1	1	5
Time to produce 14,400 blades/mo	23.75 d	24.53 d	24.77 d	25.1-25.3 d	25 d	25 d
Maintenance time/mo	6.25 d	5.47 d	5.23 d	4.9-4.7 d	5 d	5 d
Power required/furnace or coils (kw)	5 to 10	5 to 10	5 to 10	3	2	10
Total power required (kw)	80 to 160	750 to 1500	1080 to 2150	24	16	80
Materials storage system						
No. of racks/furnace	1	1	1	3	2	2
No. of compartments/rack				25	30	30
No. of molds/furnace	900	96	68	600	300	300
No. of blades/furnace/mo.	900	96	68	1800	1800	1800
Average allowable mold density at 2 lb/blade (g/cm^3)				8.2	8.5	8.5
Materials handling equipment needed	yes	yes	yes	yes	yes	yes
Space (volume) to house facilities per furnace system (m^3)				37.5	19.2	13.4
Total system (m^3)	excessive	excessive	excessive	300	153.2	107.5
No. of units to be handled/total system	14,400	14,400	14,400	600	480	480
Total No. of unit to be handled during r furbishment	28,800	28,800	28,800	1200	960	960
Cooling Control	movement of coils	movement of coils	movement of coils	furnace temp. control	gas or liquid	gas or liquid

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4.2 Introduction

The average projected demand of space processed turbine blades is 160,200 per year or 13,350 per month. A reasonable rejection rate of 7.3 percent increases the number required to 172,800 per year or 14,400 per month. Eutectic directional solidification of this number of blades at the necessary low solidification rates of the order of 0.5 in/hr (0.00353 mm/sec) or less [1] requires a long process time and several furnaces. Also a great deal of storage facilities and electrical power are needed. With a cargo weight of 32,000 pounds and limited time for a shuttle trip, the weight of the necessary manufacturing facilities, the weight of the large volume of blades required, and the time required to produce these blades eliminates the use of a shuttle for blade processing. Thus, a permanent space factory is necessary to produce the required blade volume. The shuttle is seen as only a means of maintenance and refurbishment of a permanent space factory with a shuttle trip every month.

Economically, space processing should involve only a few simple procedures. Therefore, space processing of turbine blades should be nothing more than a simple re-melt operation. The envisioned process involves the following steps or procedures performed on earth and in space:

a. Earth processing (pre-space)

1. Manufacture of pre-cast blades
2. Manufacture of space molds (likely ceramic type) for the re-melting of blades in space
3. Positioning of pre-cast blades in space molds
4. Assembly of materials in space storage package
5. Shipment to launch site
6. Preparation for launch
7. Shuttle transportation to space factory once a month

b. Space processing

8. Refurbishment and maintenance of space factory by crew

9. Re-melt of blades under controlled space conditions over a period of approximately 25 days

c. Earth processing (after space)

10. Return shuttle transportation to earth after four to five days of maintenance and refurbishment

11. Shipment of finished blades to manufacturer

12. Removal of blades from space molds and inspection thereof.

The initial criterion outlined in this report for space processing of turbine blades is based on data generated by G.E. [1] for containerless melting. This data is reproduced in Table 4-2. The blade under consideration is for the JT-8D and RB-211 type engines. This blade is shown in Figure 4-1.

On the basis of the total process time per blade in Table 4-2, the number of furnaces and the time required to produce 14,400 blades per month are shown in Table 4-3. This latter table considers a batch process in which one blade at a time is produced in each furnace. With a minimum time of 62 minutes per blade, 25 furnaces are required to produce enough blades in the required time span and leave sufficient time for maintenance and refurbishment in each period of 30 days. The maximum time of 370 minutes for processing each blade requires on the order of 125 furnaces and no time for maintenance and refurbishment. Both of these times involve rates much faster than the 0.5 in/hr. Thus, it is seen from Table 4-3 that a batch process producing one blade per furnace at a time is neither realistic, practical or economical. Therefore, it is evident that either a continuous type furnace operation or a multi-batch

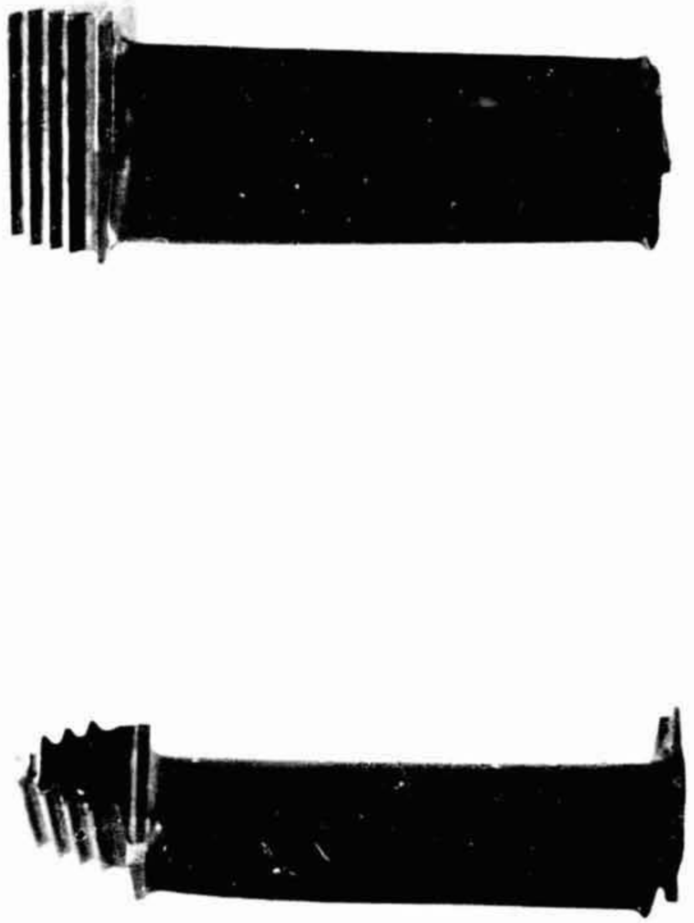


FIGURE 4-1: TWO VIEWS OF TURBINE BLADE USED IN THE JT-8D AND RB-211 TYPE ENGINES

TABLE 4-2: TURBINE BLADE PROCESSING REQUIREMENTS [1]

BASED ON CONTAINERLESS MELTING

Preheat	
high rate	10-100 C/sec
low rate	5-10 C/sec
Maximum temperature	1560 C
Dwell temperature	1560 C
Cooling rate	0.02-0.05 C/sec
Time to produce dwell	0.5-5 min
Time at dwell (solid)	0 min
Time to melt and superheat	0 min
Time at dwell (molten)	1-5 min
Time to cool to recovery	60-360 min
Total time	61.5-370 min

TABLE 4-3: FURNACE AND TIME REQUIREMENTS TO PRODUCE 172,800 TURBINE BLADES PER YEAR

Assumptions:
172,800 units/year or 14,400 units/month
12 trips/year for maintenance and refurbishment
30 days/month

Furnace Time per Unit (Minutes)	No. of Furnace Required	Unit Per Furnace Per Month	Production Time Per Month (Days)	Maint. Time Per Month (Days)	Maint. Time Per Year (Days)	Total Units Per Year
62 (Minimum)	20	690	29.7	0.3	3.6	165,600
	25	576	24.8	5.2	62.4	172,800
	30	480	20.7	9.3	111.6	172,800
370 (Maximum)	125	115	29.5	0.5	6.0	172,500
	150	96	24.6	5.4	62.8	172,800

process is necessary to produce the large number of blades. Thus, this report evaluates three different possible furnace processes: (a) induction melting of single blades, (b) continuous resistance type of furnaces for multi-blade molds, and (c) batch resistance type furnaces for multi-blade molds. In all three cases, the blade or blades must be encased in a mold to obtain the desired blade shape and dimensions. Containerless melting cannot produce the required complex blade shape because of the surface tensions of the molten alloy.

4.3 Induction Melting

The use of induction melting techniques at first glance seems to be one of the possible methods of producing turbine blades in space. This method would allow the use of a seed crystal since the heating cycle would not begin until the blade was positioned correctly in the coils. With the use of automatic handling equipment, the mold and blade could be positioned exactly in the coils without regard to the length of the mold, and thus, reduce the total process time. Precise control of the heating and cooling cycles, the length of the molten zone and the solidification rate could be maintained at all times. This control generally could be done by coil length, the rate of blade travel through the coils (and thus solidification rate) and the variation of electrical power.

Table 4-4 gives the approximate requirements necessary to produce 14,400 blades per month by induction melting. The time required to produce these blades is a function of the blade rate of travel through the coils and the length of the blade. The coil length is assumed to be less than the blade length. Three rates of travel - 0.05, 0.005, and 0.0035 mm/sec (7.1, 0.71 and 0.496 in/hr, respectively) were analyzed. The latter rate of 0.0035 mm/sec was chosen because it is in the range necessary for the directional solidification of high melting eutectics, such as in the Ni-Ta system [2]. The other rates were selected because they are in the range which have been used for some of the lower melting eutectics, such as Al-Cu [3].

Table 4-4 indicates that induction melting will require too many furnaces and too much power to be considered either economically or technologically feasible. The reason being the combination of (a) the

TABLE 4-4: INDUCTION MELTING REQUIREMENTS FOR TURBINE BLADES

Item	Solidification Rate		
	0.05 mm/sec (7.1 in/hr)	0.005 mm/sec (.71 in/hr)	0.0035 mm/sec (.496 in/hr)
Length of blade travel through coils or blade length (mm)	110	110	110
Time to produce each blade (min)	36.67	366.7	523.3
Time interval between blades (minutes)	1.33	1.3	1.3
(seconds)	80	78	78
Number of blades produced per furnace in approximately 25 days	900	96	68
Total number of days to produce above blades	23.75	24.53	24.77
Total number of furnaces required to produce 14,400 blades	16	150	215
Power required per furnace (kw)	5 to 10	5 to 10	5 to 10
Total power required (kw)	80 to 160	750 to 1500	1080 to 2150

probably inability of producing more than one blade at a time per furnace and (b) the time necessary to produce each blade. The only way induction melting can be feasible under these conditions is the use of high solidification ra:es on the order of 7.1 in/hr (0.05 mm/sec) or greater and or multi-coil units. The latter would reduce the number of induction units but not the power requirements. Total space necessary to house these induction units and the associated materials storage and handling facilities would be excessive.

4.4 Resistance Furnaces

4.4.1 Continuous Operation

4.4.1.1 Assumptions

The development of a continuous system involves the consideration of the type of blade mold (design), materials storage facility, furnace design, materials handling equipment, total space required to house the facility and the allowable density of the mold material. Consideration must be given not only to the space factory but also to the cargo weights involved during each shuttle trip. In an effort to outline the minimum system required for a possible permanent space factory for the production of turbine blades, the following assumptions were made to define the initial boundary conditions of a continuous furnace system.

a. A minimum of 14,400 blades per month instead of 13,350 must be produced to allow for at least a rejection rate of 1050 blades per month or 7.3 percent.

b. This volume of blades should be produced in approximately 25 days out of every 30 to allow sufficient time for maintenance and refurbishment by the shuttle crew.

c. One complete shuttle trip of seven days or less in every 30 day period.

d. Space processing of the blades consisting of a simple re-melt operation of pre-cast blades.

e. Expendable mold (possibly ceramic type) for the re-melting of the blades in space.

f. Each re-melt mold capable of containing several blades (multi-blade molds).

g. Because the shuttle cargo load is 32,000 pounds, the total maximum allowable weight of blades, molds and storage system is 2 pounds (908 gm) per blade for a total of 28,800 pounds.

4.4.1.2 Molds

Processing 14,400 blades per month in a reasonable number of continuous furnaces necessitates the development of a re-melt mold capable of holding several blades. The mold material must be capable of being cast or otherwise formed to close dimensional tolerances into a thin-walled, complex shape without internal defects (a shell-type mold). Each mold will have to be made in two halves to facilitate positioning of the pre-cast blades in the mold.

A number of factors must be considered when determining the number of blades which can be produced per mold. These factors are:

a. Time required to process 14,400 blades and leave sufficient time in each 30-day period for maintenance and refurbishment;

b. The number of furnaces required;

c. The size of the furnace with respect to maintaining a constant temperature over the width of the furnace;

d. The size of the mold which determines the furnace size;

e. The number of molds which can be processed by a single furnace in the required time;

f. The available storage space for the molds which are produced by a single furnace.

Table 4-5 shows the relationship between the number of blades per mold, the number of molds required to be processed per furnace, and the number of furnaces required.

To have sufficient time for maintenance and refurbishment in every 30-day period by the shuttle crew, 25-26 days (600-624 hours) of continuous furnace operation was selected as the optimum process time. Twenty-five to twenty-six days of operation gives full usage of time without leaving the equipment idle for long periods. This time also reduces the number

TABLE 4-3: RELATIONSHIP OF BLADES PER MOLD TO THE NUMBER OF MOLDS AND FURNANCES REQUIRED TO PRODUCE 14,400 BLADES PER MONTH

Blades per Mold	Molds per Furnace	Time to Produce (hr)	No. of Furnaces Required	No. of Blades per Month
1	480	488	30	14,400
2	480	488	15	14,400
3	480	488	10	14,400
4	480	488	8	15,360
5	480	488	6	14,400
1	540	548	26	14,240
2	540	548	13	14,240
3	540	548	9	14,580
4	540	548	7	15,120
5	540	548	6	16,200
1	600	608	24	14,400
2	600	608	12	14,400
3	600	608	8	14,400
4	600	608	6	14,400
5	600	608	5	15,500
1	640	648	23	14,720
2	640	648	12	15,360
3	640	648	8	15,360
4	640	648	6	15,360
5	640	648	5	16,000

of blades per mold which have to be processed and thereby reduces the overall furnace size required. The furnace size also was considered to be too large to easily maintain the required temperature across the furnace width when more than five blades per mold are used. Therefore as a result of the above reasoning, three blades per mold, 600 molds per furnace, and eight furnaces were selected as the basis for the systems design in this report.

The mold under consideration is designed so that the blade cavities are parallel to each other to allow all three blades to be processed simultaneously. With this arrangement, the width of the mold is greater than the length. The mold length is a little longer than the length of a single blade, while the mold width is greater than the width of three blades. The direction of movement of the mold through the furnace is parallel to the mold length. Table 4-6 gives the overall dimensions of a single blade and mold. These mold dimensions were determined as follows:

$$\begin{aligned}
\text{Mold length} &= \text{blade length} + (25\text{ mm per end})(2\text{ ends}) \\
&= 110 + (25)(2) \\
&= 160\text{ mm} = 16\text{ cm}
\end{aligned}$$

$$\begin{aligned}
\text{Mold width} &= (\text{No. of blades})\ [\text{blade width} + (12\text{ mm per blade size}) \\
&\quad (2\text{ sides})] + (12\text{ mm per mold side})(2\text{ sides}) \\
&= (3)\ [43 + (12)(2)] + (12)(2) \\
&= 225\text{ mm} = 22.5\text{ cm}
\end{aligned}$$

$$\begin{aligned}
\text{Total mold height} &= \text{blade height} + (\text{mold thickness per half mold}) \\
&\quad (2\text{ halves}) \\
&= 32 + (3)(2) \\
&= 38\text{ mm} = 3.8\text{ cm}
\end{aligned}$$

Other properties of the mold which must be considered other than size and castability or formability of the mold material, are thermal conductivity, thermal shock resistance, mechanical strength, density and cost. High thermal conductivity of the mold is necessary to allow rapid

TABLE 4-6: RE-MELT MOLD DIMENSIONS FOR CONTINUOUS SYSTEM

Number of blades per mold	3
Blade dimensions	
Maximum length	11 cm
Maximum width	4.3 cm
Maximum height	3.2 cm
Spacing (minimum) between blades	2.4 cm
Extra mold dimensions outside of blade region	
width, each side	1.2 cm
length, each side	2.5 cm
Thickness of mold wall	0.3 cm
Overall dimensions of mold	
width	22.5 cm
length	16 cm
height (maximum)	3.8 cm

heating and controlled cooling of the blades during the process cycle. Good thermal sho . resistance is required to prevent thermal spalling or cracking of the mold during the rapid heating cycle. Excellent mechanical strength is required to prevent breaking, spalling or cracking as a result of stresses imposed during shuttle launch or during handling by human or mechanical means prior to the process cycle. The mold material and mold fabrication must be of low cost because in all likelihood most molds will be broken during removal of blades after processing and thus cannot be reused. The molds should be expendable. Weight of the molds is important during shuttle launch but as will be seen later, the density of the mold material may not be a confining factor in the selection of the material. The low weight and high thermal conductivity of the molds dictates a thin-walled mold.

4.4.1.3 Furnaces

The type of continuous furnace system set forth in this report for preliminary consideration for the production of turbine blades in space is based on the following assumptions:

a. Open-end type furnace

b. Unpressured space chamber during process cycle

c. Continuous conveyer system to move the molds through the furnace at the desired rate

d. Total time of blades (not molds) in furnace chamber as either 61.5 or 370 minutes (from Table 4-2)

e. Controlled cooling occuring within the furnace chamber

f. Refractory thickness of 15 cm on all sides of the furnace

g. Furnace chamber width and height dependent on mold size

h. Furnace system length equal to length of conveyer

i. Furnace system divided into seven zones:

   1) Loading zone of conveyer - where mold is loaded mechanically

   2) Preheat zone - region of refractory at front end of furnace

   3) Heating zone - blade brought to temperature

   4) Dwell zone - blade held in molten state

   5) Cooling zone - controlled cooling rate for directional solidification

   6) Post cooling zone - region of refractory at rear of furnace

   7) Unloading zone of conveyer - mold unloaded mechanically

j. Process time for a given blade is based on the time of travel of the mold through the entire length of the conveyer system and not the time the blade is in the controlled hot zones

k. Dimensions of furnace chamber based on time that any small element of the blade and not the entire blade is in the chamber

l. Portions of the blade may be in the heating, dwell and cooling zones simultaneously

m. Rate of mold travel through furnace as 0.05 mm per sec (7.1 in/hr)

This last assumption is based on the physical need of a finite furnace length and a reasonable rate of sample movement. The inside chamber length of the furnace and the rate of mold travel was selected as follows:

Assume:

a. Chamber length of furnace is equal to length of heating zone plus length of dwell zone plus length of cooling zone.

b. Time of blade in chamber is equal to the time from entrance of front end of blade to exit of rear end of blade. Therefore, total length of travel of any small blade element is equal to the furnace chamber length plus blade length or $L = f + 110$ mm where f is the furnace chamber length.

c. Total length of travel of any small blade element also is equal to the product of the time of travel and the rate of travel or $L = (t)(R)$

d. Minimum time as 61.5 min or 36.9×10^2 sec [1]
Maximum time as 370 min or 22.2×10^3 sec [1]

e. Normal rates for eutectic directional solidification have varied between 0.0068 and 0.14 mm per sec [2,3]. Thus, to cover this range, three rates 0.1, 0.05 and .005 mm per sec were evaluated.

From assumptions (b) and (c).

$$f + 110 \text{ mm} = (t)(R)$$

$$f = (t)(R) - 110$$

For R = 0.1 mm per sec

$t = 61.5$ min; $f = 25.9$ cm

$t = 370$ min; $f = 211$ cm

For R = 0.05 mm per sec

$t = 61.5$ min; $f = 7.45$ cm

$t = 370$ min; $f = 100$ cm

For R = 0.005 mm per sec

$t = 61.5$ min; $f = -9.2$ cm

$t = 370$ min; $f = 0.1$ cm

The rate of 0.005 mm per sec is impracticable for the specified times. Of the two remaining rates, 0.05 mm per sec was selected because in general the best results are obtained during directional solidification with the slowest rate. The faster the rate, the greater the possible vibration and chance for additional and unwanted nucleation.

The overall furnace system cannot consist solely of the furnace chamber. Provisions must be made for refractory at each end of the chamber to minimize heat loss. Also, some means of loading and unloading of the furnace must be provided. For a continuous type furnace, a conveyer system must be used to move the product through the furnace. The minimum length of this conveyer system is equal to the sum of the furnace chamber, the refractory thickness at each end of the chamber, and sufficient length at each end for loading and unloading the molds. Based on the original assumptions and a blade travel rate of 0.05 mm/sec, the overall furnace and conveyer dimensions required are given in Table 4-7. Figure 4-2 shows a diagram of the proposed furnace system. The length of the heating and dwell zones are quite small but can be changed within the overall furnace dimensions, depending upon the required temperature gradient in the cooling zone. The length of each zone was determined on the basis of time and not temperature gradient. The length of 20 cm for the loading and unloading zones is based on a mold length of 16 cm. The furnace chamber width and height were determined from the following relationships:

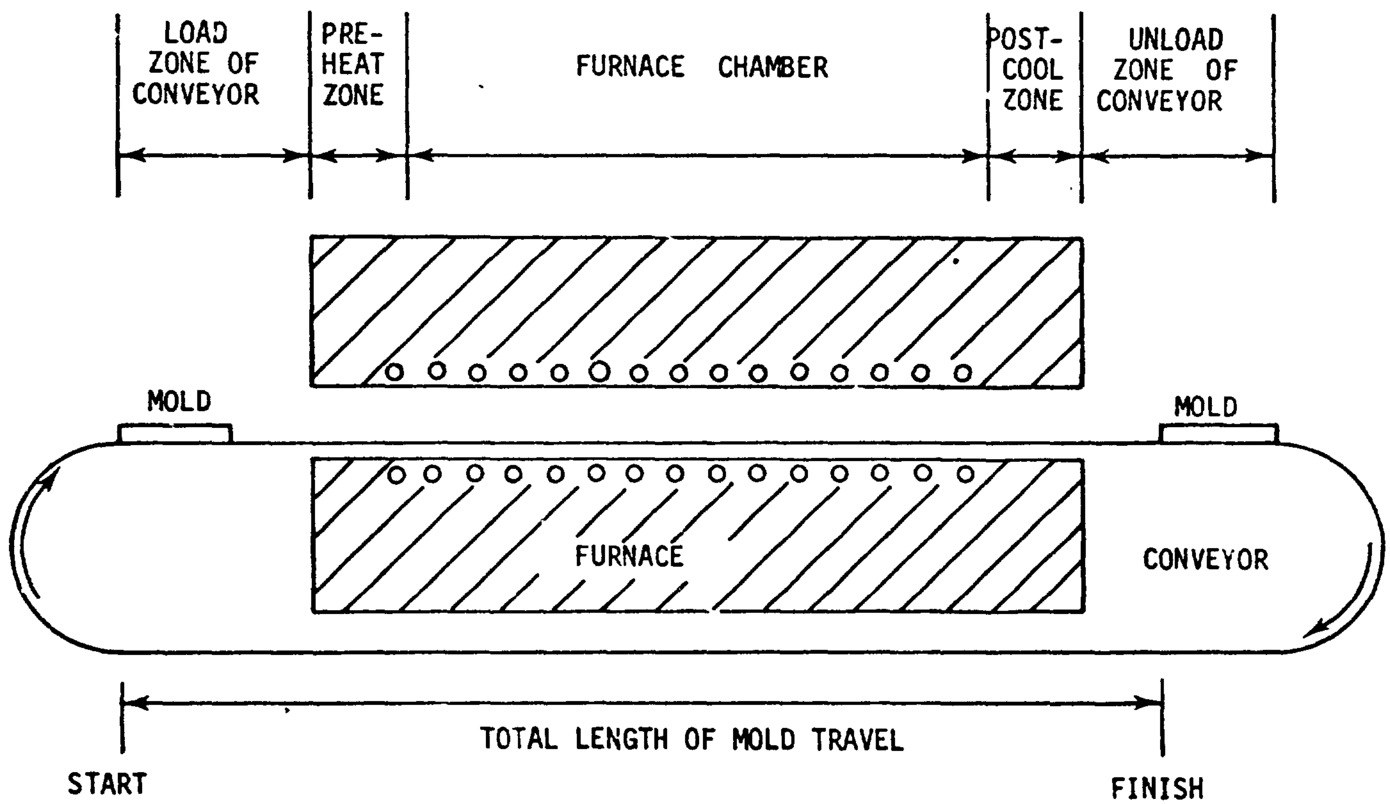


FIGURE 4-2: DIAGRAM OF PROPOSED CONTINUOUS TURBINE BLADE PROCESS FURNACE SYSTEM.

TABLE 4-7: FURNACE SYSTEM AND TIMES REQUIRED TO PRODUCE 14,400 BLADES PER MONTH

Furnace dimensions based on mold size from Table and rate of mold travel of 0.05 mm/sec	Dimensions based on time of blade in controlled furnace zones: 370 min	61.5 min
Total length of system	170.00 cm	77.50 cm
A. Loading zone of conveyer	20.00 cm	20.00 cm
B. Preheat zone (refractory thickness)	15.00 cm	15.00 cm
C. Furnace chamber	100.00 cm	7.45 cm
1. Heating zone	1.50 cm	0.18 cm
2. Dwell zone	1.50 cm	0.36 cm
3. Cooling zone	97.00 cm	6.91 cm
D. Post cooling zone (refractory thickness)	15.00 cm	15.00 cm
E. Unloading zone of conveyer	20.00 cm	20.00 cm
Inside furnace chamber dimensions		
Width	25.00 cm	25.00 cm
Height	7.00 cm	7.00 cm
Refractory thickness on all walls	15.00 cm	15.00 cm
Overall furnace dimensions		
Width	55.00 cm	55.00 cm
Height	37.00 cm	37.00 cm
Total length of mold travel	154.00 cm	61.50 cm
Time for mold to traverse system	8.55 hr	3.4[illegible] hr
Time for 600 mold/furnace or 1,800 blades (one mold/hr)	25.30 days	25.10 d
Time for maintenance and refurbishment in every 30 days	4.70 d	4.90 d
No. of furnaces required to produce 14,400 blades/month	8	8

$$\text{chamber width} = \text{mold width} + 2.5 \text{ cm}$$

$$= 22.5 + 2.5 = 25 \text{ cm}$$

$$\text{chamber height} = \text{mold height} + \text{assumed conveyer thickness}$$

$$= 3.8 + 3.2 = 7 \text{ cm}$$

The length of mold travel is equal to the conveyer length minus the mold length (Figure 4-2).

Table 4-7 also gives the times required for each furnace to process 600 molds or 1800 blades. This time is based on loading a mold on the conveyer every hour (60 minutes) and on the following relationships.

$$\frac{\text{Time for one mold}}{\text{to traverse system}} = \frac{\text{length of mold travel}}{\text{rate of travel}}$$

$$\text{Total time to process 600 molds} = (\text{time for one mold}) + (599)(1 \text{ hr for each additional mold})$$

It is interesting to compare the process times of 370 and 61.5 minutes in the controlled temperature zone using a continuous conveyer and loading a mold on the system every hour. Under these conditions, the overall time required to produce the necessary blades differs only by the difference in time (0.2 days) for the first mold to completely traverse the conveyer system, regardless of the time in the controlled furnace region. In either case, a minimum of eight (8) furnaces are required to produce a total of 14,400 blades per month. The only difference between the systems is the furnace length required. As will be seen later, it is not the furnace size but the size of the storage system required for 600 molds per furnace or a total of 4800 molds which is the main factor in determining the amount of space (volume) needed per continuous furnace system in the space factory.

The rate of 0.05 mm/sec (7.1 in/hr) is probably too fast for the high melting eutectics useable for turbine blades and will in all likelihood eliminate a continuous resistance furnace system under the assumed conditions. However, it may be technically possible to use faster solidification rates at zero gravity. Also, with different boundary conditions of time and furnace size, the basic continuous furnace concept may be useable. Therefore, consideration is given to the entire facility required for a continuous process because the furnace seems to be the smallest item in size.

4.4.1.4 Materials Storage System

The production of 14,400 blades at three per mold requires a total of 4,800 molds. With the use of eight furnaces, 600 molds per furnace have to be handled and stored. A possible materials storage system (hereafter called "racks") can take many different shapes or designs. However, to conserve space in the factory, a "circular-type" rack system for each furnace was selected. This system in reality consists of three rectangular racks in a triangular arrangement on a revolving circular base (Figure 4-3). Each rack is capable of holding 200 molds.

For ease of crew handling during refurbishment, each rack is subdivided into removable compartments or subracks. Each compartment contains eight (8) molds. Each rack then consists of 25 compartments (5 by 5). The subdivision of the racks into removable compartments allows the 4,800 molds to be handled as 600 units. This general type of multi-mold handling is necessary because, if each individual mold is handled, a total of 9600 units on each shuttle trip would have to be moved between the shuttle and the factory. The use of removable compartments means only 1200 units need be handled.

The general configuration of both the removable compartments and a single rack are shown in Figures 4-4 and 4-5. The design of the entire rack system is based on the use of either a Boron-Aluminum composite or the LA141-A alloy. The latter is a lightweight alloy containing 14% lithium, 1% aluminum and the balance magnesium. Because of the strength difference between these two materials, slightly different dimensions are required in each case. The design dimensions used for the compartments and racks are shown in Tables 4-8 and 4-9, respectively.

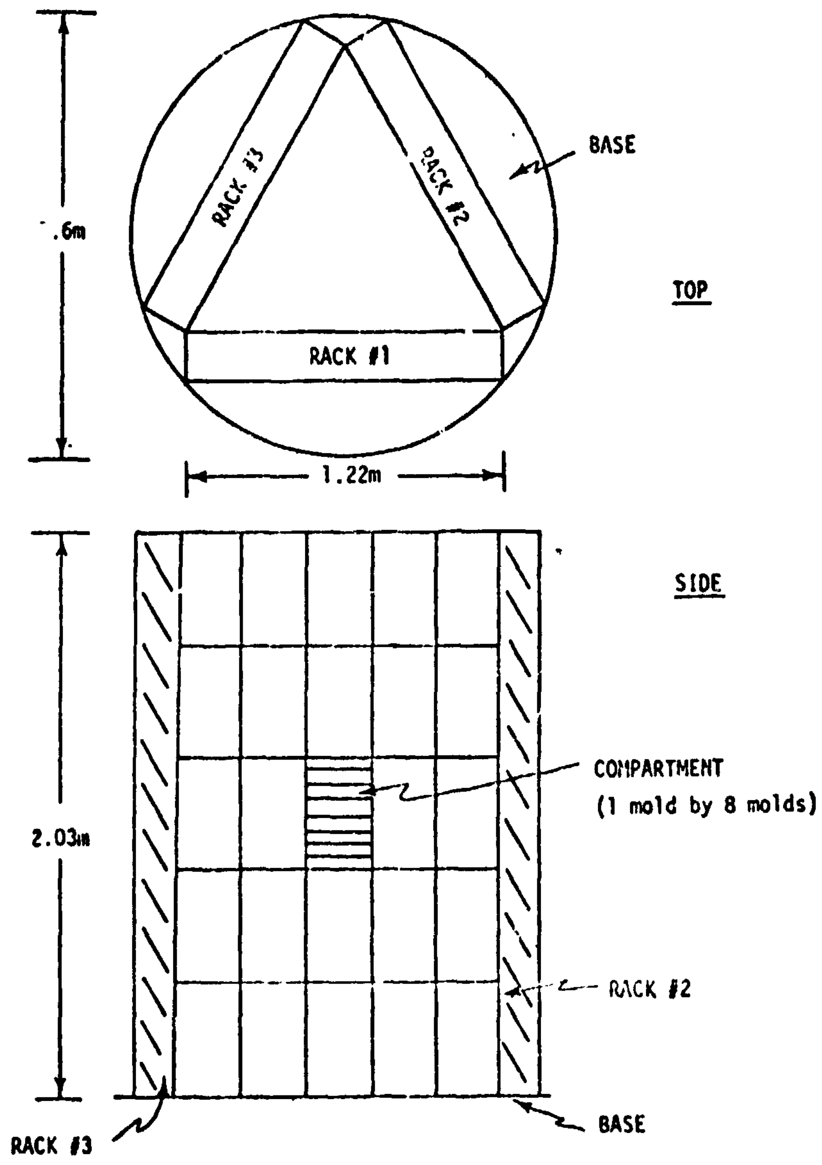


FIGURE 4-3: POSSIBLE MATERIALS STORAGE SYSTEM FOR CONTINUOUS FURNACE

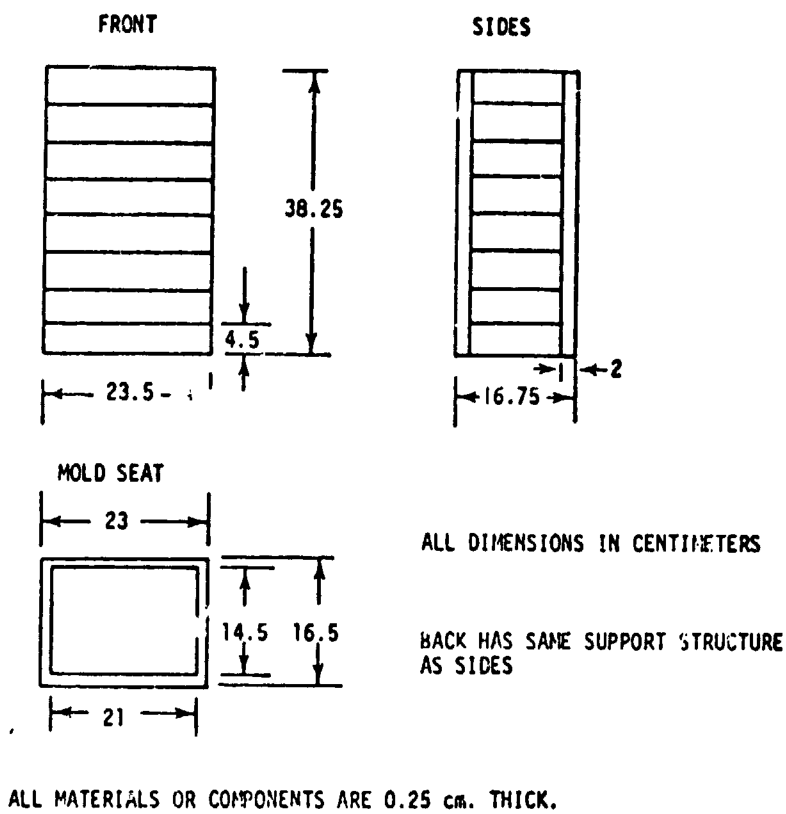


FIGURE 4-4: DIAGRAM OF REMOVAL COMPARTMENT IN RACK SYSTEM FOR CONTINUOUS FURNACE

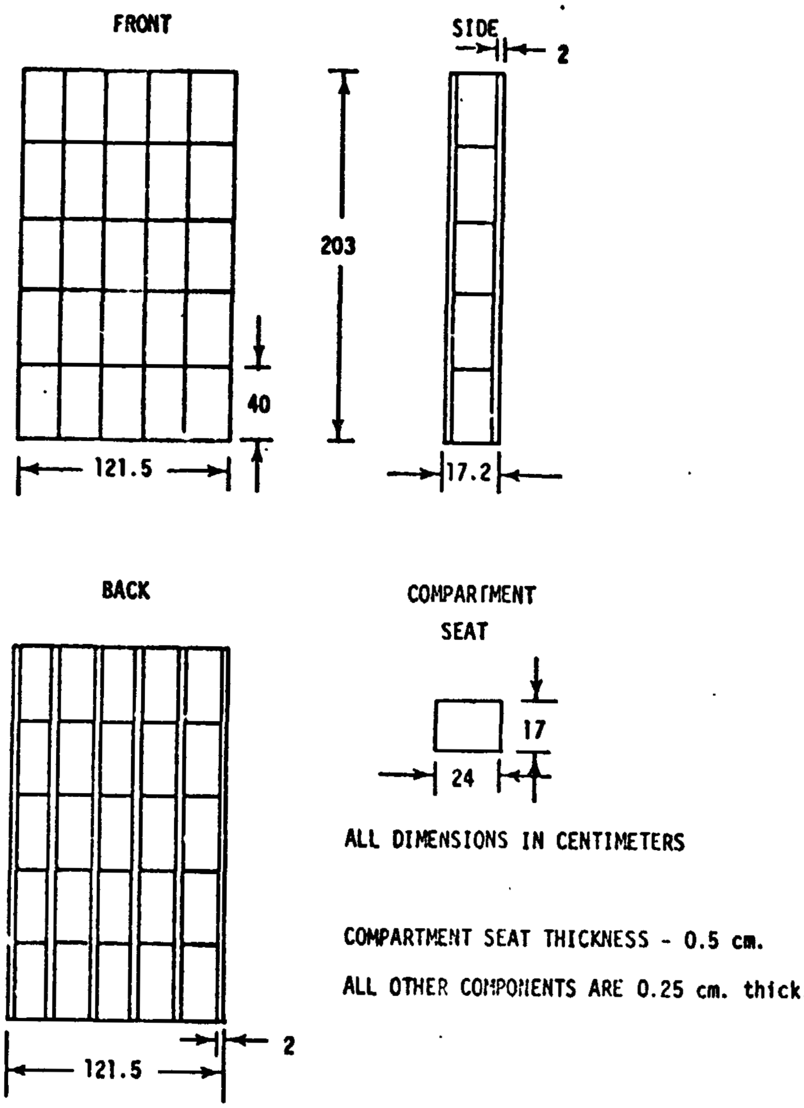


FIGURE 4-5: DIAGRAM OF RACK SYSTEM FOR CONTINUOUS FURNACE

TABLE 4-8: REMOVABLE COMPARTMENTS OR SUBRACKS

	B-Al	LA141A
Mold seat dimensions		
Outside		
Width (cm)	23	23
Depth (cm)	16.5	16.5
Inside		
Width (cm)	21	21
Depth (cm)	14.5	14.5
Thickness (cm)	0.25	0.5
Number of seats including top	9	9
Volume of seats (cm^3)	168.8	337.5
Vertical distance between seats (cm)	4.5	4.5
Vertical supports		
Width (cm)	2	2
Thickness (cm)	0.25	0.25
Length (cm)	38.25	40.5
Total number	6	6
Total volume (cm^3)	57.4	121.5
Total volume of material in one compartment (cm^3)	226.2	459
Total volume of material in 25 compartments (1 rack) (cm^3)	5,655	11,475
Overall dimensions of each compartment		
Width (cm)	23.5	23.5
Depth (cm)	16.75	16.75
Height (cm)	38.25	40.5
Yeild stress (UTS for B-Al) (psi)	10^5	15×10^3
Maximum load 6 supports can carry (lb)	46.5×10^3	6.98×10^3
Maximum allowables wt. @ 2 lb/blade (lb)	48	48
Load at 10 G's (lb)	480	480

TABLE 4-9: RACK REQUIREMENTS

	B-Al	LA141A
Compartment seat dimensions		
Width (cm)	24	24
Depth (cm)	17	17
Thickness (cm)	0.5	0.5
Number including top	30	30
Distance between seats (cm)	40	40
Volume of material in seats (cm^3)	6,020	6,020
Vertical supports		
Width (cm)	2	2
Thickness (cm)	0.25	0.25
Length (cm)	203	213
Number of supports	18	18
Total volume of supports (cm^3)	1,827	1,917
Total volume of material in one rack (cm^3)	7,847	7.937
Overall dimensions of one rack		
Width (cm)	121.5	121.5
Depth (cm)	17.25	17.25
Height (cm)	203	213
Diameter of circular base (cm)	160.36	160.35
Maximum load supports can carry (lb)	139,500	21,925
Maximum allowable wt. @ 2 lb/blade (lb)	1,200	1,200
Load at 10 G's	12,000	12,000

Appendices A and B illustrate how all values in Tables 4-8 and 4-9 were determined. Appendix D shows the method for determining the diameter of the circular rack base.

Also shown in these Tables is a comparison of the maximum load each system can carry to the maximum expected load during launch of a shuttle. Similar rack systems must be present in the shuttle as well as the space factory. The maximum expected load is based on a maximum load of two pounds total weight per blade (14,400 x 2 = 28,800). The cargo shuttle load is only 32,000 pounds. The load on various members during launch is considered to be ten (10) times the static load. The maximum load each system can carry is based on the simple relationship:

Stress = load/area

The load is assumed to be divided equally between all vertical support members. This assumption is not strictly correct but is sufficient for these calculations and for the determination of allowable mold density which is discussed later. It is evident in the case of both the compartments and rack that the system is over-designed with respect to the cross-sectional area of the vertical supports. This is intentional in order to be sure that all systems are within the allowable cargo weight on each shuttle trip and to withstand launch vibrations.

4.4.1.5 Materials Handling Mechanism

A summary of the number of racks, compartments and molds required by eight continuous furnaces to process 14,400 blades in less than 30 days is given in Table 4-10. A total of 600 molds per furnace must be automatically moved from the racks to the furnace conveyer and then replaced after processing. Thus a computerized materials handling mechanism must be employed. The computer system also must control the circular movement of the racks as required.

Either of two methods can be utilized to move the molds between the racks and the conveyer system. The first method involves moving compartments as units back and forth, positioning of compartments at either end of the conveyer, removing the molds from and replacing them in the compartments. Also involved is the mechanisms required for locking and unlocking the molds to the conveyer. This method would be quite complex because on the order of 13 to 15 individual steps would be necessary.

The second method involves handling of each individual mold directly from the rack. This method would require less complex equipment and computer programming. The envisioned procedures required to process individual molds directly from the rack involves:

a. Unlocking the mold in the compartment;

b. Removal of mold from compartment in the rack;

c. Moving the mold to the start of the conveyer;

d. Locking the mold to the conveyer;

e. Unlocking the mold from the conveyer at the end of the process;

f. Moving the mold back to the rack;

TABLE 4-10: SUMMARY OF MATERIALS STORAGE SYSTEM AND FURNACES REQUIRED TO PRODUCE 14,400 BLADES IN 30 DAYS

Number of racks/furnace	3
Number of compartments/rack	25
Number of compartments/furnace	75
Number of molds/compartment	8
Number of molds/rack	200
Number of molds/furnace	600
Number of blades/mold	3
Number of blades/furnace	1,800
Total number of furnaces	8
Total number of racks/8 furnaces	24
Total number of compartments/8 furnaces	600
Total number of molds/8 furnaces	4,800
Total number of blades/8 furnaces	14,400

g. Positioning of the mold in its initial place in the rack;

h. Locking the mold in place.

One materials handling mechanism per furnace is required. The time sequence will be such that the mold removal and replacing steps should not interfere with each other. However, for efficient operation, the rotating rack system must be reversible. The time sequence of events is such that the rack for continued removal of the molds before the first rack has been completely refilled with processed molds. With an interval of one hour loading time and a total process time of 8.55 hours per mold, the overlap period between two racks involves at least fourteen (14) molds (seven in each rack). The rack system must rotate back and forth between the two racks during this overlap period.

With the problem of weightlessness, a number of small devices or mechanisms need to be developed to prevent the molds from floating free in the space factory. Such devices should not be difficult to make and thus not be of technological hindrance to the development of the space factory. Some of these necessary devices are indicated below:

a. Mechanism for locking mold in the compartment. This mechanism must be capable of automatic locking and unlocking by the materials handling equipment.

b. Mechanism for locking compartments in rack. Needs only to be hand operated by the shuttle crew.

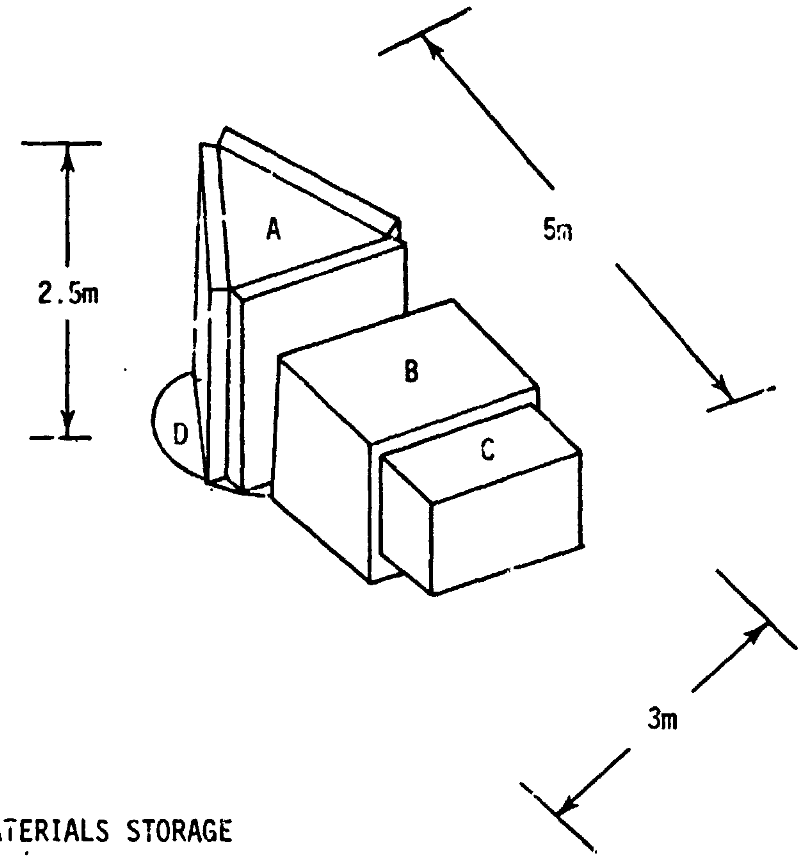
c. Mechanism for locking and unlocking mold to conveyer system. These mold locks on the conveyer system must not distort at the process temperature used. This system could be nothing more than simple hooks on the conveyer.

d. Mechanism for materials handling to move molds from racks to conveyer and then back. This could be similar to remote control equipment utilized in the nuclear industry.

4.4.1.6 Total System

The overall dimensions required for a rack system and a furnace in a continuous operation are given in Table 4-11. Also shown is the assumed "floor-space" necessary for each unit plus the materials-handling mechanism. This "floor-space" is just the dimensions required for positioning each system in the factory. It does not consider the factory space which will be required by the shuttle crew for maintenance and refurbishment.

Figure 4-6 illustrates in block form a possible arrangement of a total furnace system. Each system will require a volume of approximately 37.5 m^3 (Table 4-11). Because eight (8) furnaces or furnace systems are needed, a total volume of 300 m^3 of space is necessary to process and store 14,400 blades in less than 30 days. If the eight furnace systems are arranged in a pattern 2 high, 2 long and 2 wide, the possible space required would be 8 m (high) x 13 m (long) x 9 m (wide). This is considering 1 m between each system and 1 m crawl space around the total system. The total volume necessary is then of the order of 936 m^3. This overall volume could be reduced by increasing the number of blades per mold and thus reducing the number of furnace systems required.



A- MATERIALS STORAGE
B- MATERIALS HANDLING
C- FURNACE SYSTEM
D- CIRCULAR RACK BASE

FIGURE 4-6: BLOCK DIAGRAM OF SPACE REQUIRED FOR A SINGLE CONTINUOUS FURNACE SYSTEM.

TABLE 4-11: SPACE REQUIREMENTS IN FACTORY BASED ON FURNACE CONTROL TIME OF 370 MINUTES

	Design Dimensions	Floor Space
1. Rack		
a. Diameter of base	1.6 m	2 m
b. Height (max.)	2.13 m	2.5 m
2. Furnace conveyer		
a. Length	1.7 m	2m
b. Width	.68 m	1m
c. Height		1m
3. Material handling mechanism		
a. Length		3m
b. Width		2m
c. Height		2.5 m
4. Total System		
a. Length (1a + 2b + 3b)		5m
b. Width (3a)		3m
c. Height (1b or 3c)		2.5 m
5. Area for furnace system		15 m^2
6. Volume per furnace system		37.5 m^3
7. Total area for 8 furnace systems		90 m^2
8. Total volume for 8 furnace systems		300 m^3

4.4.1.7 Allowable Mold Density

The shuttle cargo load of 32,000 pounds restricts the combined weight of the materials storage system, molds and blades. Also, the number of blades which can be processed between shuttle trips is then limited. The production of 14,400 blades between shuttle trips restricts the maximum allowable weight for the entire system to two pounds per blade (14,400 x 2 = 28,800 lbs.). This only leaves 3200 pounds for other equipment or instruments. To prevent breakage or other damage to the molds during launch, some type of storage facility in the shuttle must be provided. Therefore, it is assumed that the same type of rack system with removable compartments as required in the factory will be used in the shuttle. This will allow direct exchange of the compartments (containing molds) between the shuttle and the factory. The only difference between the storage systems would be the arrangement of the racks in the shuttle and a circular rack base would not be required.

Under the conditions of the mold design and the materials storage system design, as already set forth, the allowable maximum mold density was calculated using three weight limitations to determine if density was a major restriction on the mold material used. The three weight limitations assumed were 1, 1.5 and 2 pounds per blade for the total system. The allowable mold density was computed on the basis of one rack. Table 4-12 gives the volume of the formed molds, the weight of the blades, the weight of the rack and compartments and the allowable mold density under each condition. The mold volume was determined by assuming a 25 percent increase in mold surface area at the blade cavities. Appendix C illustrates how all values were obtained. The density of a boron-aluminum composite

TABLE 4-12: ALLOWABLE MOLD DENSITY

	B-Al	LA141A
Total volume of material in 1 rack and 25 compartments (cm^3)	13,502	19,412
Density (gm/cm^3)	2.7	1.35
Total wt. of material in 1 rack and 25 compartments (gm)	3.65×10^4	2.62×10^4
Volume of material per mold (cm^3)	237.3	237.3
Volume of 200 molds (cm^3)	47,460	47,460
Number of blades per rack	600	600
Wt. of 600 blades @ 200 gm	12×10^4	12×10^4
Assume max. allowable wt. of 1 lb (454 gm) per blade for total system		
Max. allowable wt. (gm)	27.24×10^4	27.24×10^4
Allowable wt. for 200 molds and 1 rack system (gm)	15.24×10^4	15.24×10^4
Allowable wt. for 200 molds (gm)	11.59×10^4	12.62×10^4
Allowable mold density (gm/cm^3)	2.44	2.66
Assume max. allowable wt. of 1.5 lb (681 gm) per blade for total system		
Max. allowable wt. (gm)	40.86×10^4	40.86×10^4
Allowable wt. for 200 molds and 1 rack system (gm)	28.86×10^4	28.86×10^4
Allowable wt. for 200 molds (gm)	25.21×10^4	26.24×10^4
Allowable mold density (gm/cm^3)	5.3	5.53
Assume max. allowable wt. of 2 lb (908 gm) per blade for total system		
Max. allowable wt. (gm)	54.48×10^4	54.48×10^4
Allowable wt. for 200 molds and 1 rack system (gm)	42.48×10^4	42.48×10^4
Allowable wt. for 200 molds (gm)	38.83×10^4	39.82×10^4
Allowable mold density (gm/cm^3)	8.17	8.39

is essentially that of the aluminum alloy, and for this work, the density of aluminum (2.7 gm/cm^3) was chosen. The blade weight was obtained by weighing a single blade (199.3 gm) and for safety purposes, assumed to be 200 gms.

Regardless, whether the boron-aluminum composit or the LA141A alloy is used for the construction of the materials storage system, the allowable mold densities do not vary much under the same design conditions. When the maximum weight of one pound per blade is assumed, the mold density is restricted to about 2.4 gm/cm^3. When the weight per blade is assumed to be either 1.5 or 2 pounds, the mold density can increase to 5.3 and 8.2 gm/cm^3, respectively. In the first case, the restriction of one pound per blade could reduce the number of possible mold material candidates. However, by increasing the allowable weight to 1.5 pounds per blade, density should no longer be a factor in the selection of the mold material. It is realized that a more efficiently designed storage system and/or mold design might enable the allowable weight to be decreased to one pound per blade without imposing undue mold density restrictions. Better design could, at some later date in the program, allow either an increase in the blade production or allow shared shuttle missions. The major restrictions at this time to the selection of the mold material seems to be thermal conductivity, formability, dimensional stability and mechanical strength.

4.4.1.8 Power Requirements

A large amount of power will be required to operate eight furnaces continuously. Eventhough, peak power to heat the furnaces is required only once in every 30 day period, a high level of power is continuously required. Because the final furnace design including the refractories involved, the mold design, and the blade material have not been determined, it is difficult to estimate the electrical power requirements. Evenso, an order of magnitude of the energy required to raise the temperature of the molds and blades to the process temperature can be made. Such an estimate was made using the following assumptions:

a. Mold

1. Width - 22.5 cm
2. Thickness - 0.6 cm
3. Material - molten cast mullite
4. Density - 3.3 g/cm^3 [5]
5. Specific heat - 0.3 cal $g^{-1}K^{-1}$ [4]
6. Softening point - 3340F (1838C) [5]

b. Blade

1. Width - 4 cm (max. at base)
2. Thickness - 1.8 cm (max. at base)
3. Material - Nickel-tungsten eutectic [1] - composition - 55Ni, 45W [7]
4. Density - 11.75 g/cm^3 (calculated)
5. Specific heat - 0.15 cal $g^{-1}K^{-1}$ [6]
6. Melting point - 1502C [7]
7. Heat of fusion - 73.8 cal/g for Ni [8]
   44 cal/g for W [8]

c. Rate - .05 mm/sec

d. Change in temperature = maximum temperature - 1560C [1]

Molten cast mullite [5] was selected because of its relatively high softening point, its relatively low porosity (0.5-1%) and its dimensional stability (no appreciable change in volume at 1590-1650C). The nickel-tungsten eutectic has been suggested by G.E. [1] for containless melting. The eutectic density was calculated on the basis of the weight percent of the two elements in the alloy. Values for specific heat and heat of fusion for this eutectic alloy are unknown. However, most nickel alloys [6] have a C_p of 0.1 to 0.2 cal $g^{-1}K^{-1}$ at about 1550C so that an average value of 0.15 was assumed. The heat of fusion for the Ni-W eutectic should be between the elemental values. Thus for an order of magnitude of energy required, the highest value of the heat of fusion (for nickel) was used.

The energy necessary to raise the temperature of the mold 1560C is

$q_M = (MC_p\Delta T)\ (4.185)$

where

M = (rate) (cross-sectional area) (density)

C_p = specific heat

q_M = 1454 watts

The energy necessary to raise the temperature of the blades 1560C is

$$q_B = [(MC_p\Delta T)\ (4.185) + Mh_f\ (4.185)]\ [\text{no. of blades}]$$

$$= [(4.185)\ (M)\ (C_p\Delta T + h_f)]\ [\text{no. of blades}]$$

h_f = latent heat of fusion

q_B = 2166 watts

The total energy required per furnace to raise the temperature of both the mold and the blades 1560C is

$$q_T = q_M + q_B$$

$$q_T = 3620 \text{ watts}$$

This energy does not take into consideration any heat loss to the environment. Heat loss will be mainly by radiation since the entire system should be operated in an unpressurized factory. The use of other mold materials, mold designs, and blade alloy, may lower the energy requirements. Even so, at least 3000 watts of power per furnace system will be necessary to maintain the process. For eight furnace systems, a total of 24,000 watts of power are necessary. This is almost in the range of 10^4 to 2×10^4 watts reported by G.E. for containerless melting [1].

4.4.2 Batch Process

The batch resistance furnace process as developed is quite similar to the continuous process in that a multi-blade mold is required. However, the entire system for a batch process should be easier to design than the continuous process. The following assumptions were made in the development of the batch process.

a. The process is a simple re-melt operation.

b. The use of a mold in which the dimensions are determined in the same manner as the continuous process.

c. The requirement of an expendable multi-blade mold.

d. Total process time of approximately 600 hours to produce 14,400 blades.

e. Solidification rate as either 0.05 or 0.00353 mm/sec (7.1 and 0.05 in/hr, respectively).

f. The development of either a gas cooling system or recirculating liquid system to obtain the correct solidification rates.

g. Materials storage system or rack with removable compartments for ease of crew handling.

h. Unpressurized factory.

i. The same basic boundary conditions of maintenance time, number of shuttle trips, and shuttle cargo load as outlined in the continuous process.

Table 4-13 shows the development of the number of (a) blades per mold, (b) molds, (c) furnaces, (d) racks, and (e) removable compartments required for each solidification rate. In each case, these are the same using the assumption of approximately a total time of 1.3 hours per heat

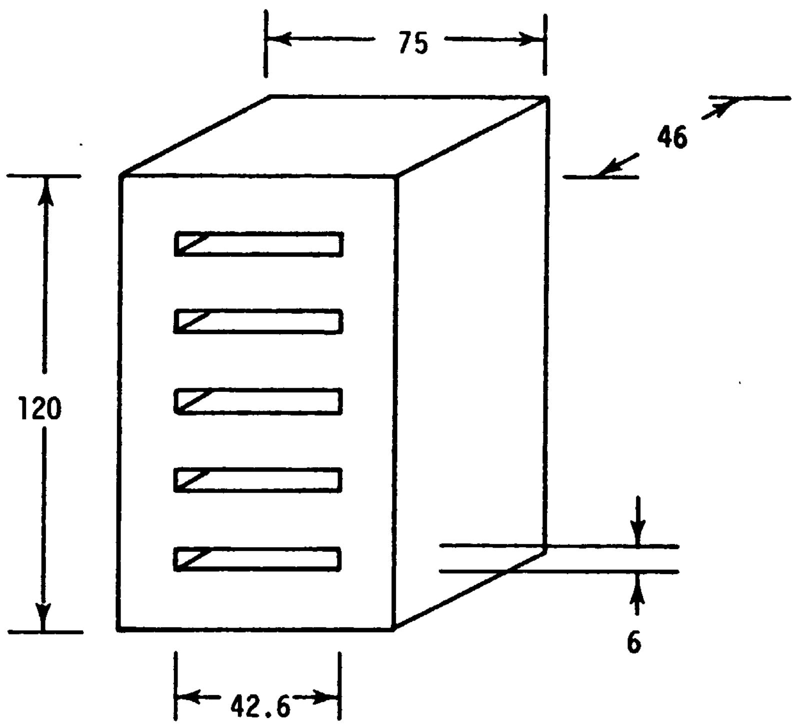
TABLE 4-13: BATCH FURNACE SYSTEM AND MOLDS REQUIRED TO PRODUCE 14,400 BLADES PER MONTH

Item	Solidification Rate .05 mm/sec 7.1 in/hr	Solidification Rate .00353 mm/sec .5 in/hr
Blade length		
cm	11	11
inches	4.33	4.33
Time of solidification/heat (hr)	.61	8.66
Assumed time for heating, dwell and materials handling/heat (hr)	1.39	1.34
Total assumed process time/heat (hr)	2	10
Total allowable processing time (hr)	600	600
No. of heats/furnace in total time	300	60
No. of furnaces	8	8
No. of blades/furnace	1800	1800
No. of blades/heat	6	30
No. of blades/mold	6	6
Required no. of heating chambers/furnace	1	5
No. of molds required/furnace	300	300
No. of racks/furnace	2	2
No. of molds/rack	150	150
No. of compartments/rack	30	30
No. of molds/compartment	5	5

for materials handling, heating and dwell. The major difference between these solidification rates is the number of heats per furnace chamber which can be made in 600 hours. With a rate of 7.1 in/hr (0.05 mm/sec), 300 heats can be made, and thus, a normal single chamber furnace can be used. Only 60 heats per furnace chamber can be made using a rate of 0.5 in/hr (0.00353 mm/sec), and a multi-chamber (5 chambers) furnace (Figure 4-7) must be utilized to produce the required number of blades. If a single chamber furnace is used for the slower solidification rate, forty furnaces instead of eight would be required. The "floor space" necessary to house forty furnaces and the associated materials handling and storage systems would be excessive.

The overall furnace dimensions depend on the mold size and the number of chambers. Table 4-14 gives the dimensions for a six-blade mold and the furnaces necessary for each solidification rate. The only difference in dimensions of the multi-chamber furnace compared to the single chamber furnace is the height (120 and 36 cm, respectively). The length and width of each furnace is dependent only on the mold size.

The materials storage system for both solidification rates is the same. Two racks per furnace with 30 removeable compartments are used. Each rack is five compartments wide, six high and one deep. Each compartment is one mold wide, five high and one deep. This combination involves 150 molds or 900 blades per rack. The compartment and rack dimensions are given in Table 4-15 and 4-16. The same general design as for the continuous process was used, except, a circular rack base is not now needed. The use of removeable compartments allows the mold to be handled in units of five during refurbishment. With 300 molds per



ALL DIMENSIONS IN CENTIMETERS

FIGURE 4-7: MULTI-CHAMBER RESISTANCE FURNACE FOR BATCH PROCESS.

TABLE 4-14: DIMENSIONS OF MOLDS AND FURNACES FOR BATCH PROCESS

Item	Solidification Rate .05 mm/sec 7.1 in/hr	Solidification Rate .00353 mm/sec .5 in/hr
Mold dimensions		
length (cm)	16	16
height (cm)	3.8	3.8
width (cm)	42.6	42.6
Surface area/mold (cm^2)	752.6	752.6
Volume/mold (cm^3)	451.5	451.5
No. of molds/rack	150	150
Total mold volume/rack (cm^3)	67.73×10^3	67.73×10^3
Dimensions of each furnace chamber		
width (cm)	45	45
height (cm)	6	6
depth (cm)	16	16
Refractory thickness on all walls (cm)	15	15
No. of furnace chambers	1	5
Overall furnace dimensions		
length (cm)	46	46
width (cm)	75	75
height (cm)	36	120

TABLE 4-15: DIMENSIONS OF COMPARTMENTS FOR BATCH PROCESS

Item	Dimensions
Mold seat	
width (cm)	43 (41)
depth (cm)	16.5 (14.5)
height (cm)	4.3
thickness of seat (cm)	.5
No. of mold seats including top	6
No. of required vertical supports	6
length (cm)	24.5
width (cm)	2
thickness (cm)	.5
Overall dimensions	
width (cm)	44
depth (cm)	17
height (cm)	24.5
Volume/mold seat (cm^3)	57.5
Volume of 6 seats (cm^3)	345
Volume/support (cm^3)	24.5
Volume of 6 supports (cm^3)	147
Volume/compartment (cm^3)	492
Total volume of 30 compartments (cm^3)	14.8×10^3

( ) Inside dimensions of mold seat. Mold seat is a frame.

TABLE 4-16: DIMENSIONS OF RACK FOR BATCH PROCESS

Item	Dimensions
Compartment seat	
width (cm)	44.5
depth (cm)	17
height (cm)	25
thickness of each seat (cm)	.5
No. of seats including top	35
Volume of compartment seat (cm^3)	388
Total volume of seats (cm^3)	132.39×10^2
Required no. of vertical supports/rack	18
Width of support (cm)	2
Thickness of support (cm)	.5
Length of support (cm)	153.5
Volume/support (cm^3)	153.5
Volume of 18 supports (cm^3)	2763
Overall rack dimensions	
width (cm)	225.5
depth (cm)	17.5
height (cm)	153.5
Total volume/rack (cm^3)	160.02×10^2
Total volume of rack and 30 compartments (cm^3)	30.76×10^3

furnace a total of 4800 molds must be handled during refurbishment. Using removeable compartments containing five molds each, a total of only 960 units must be moved both ways between the shuttle and factory.

To simplify the calculations of the volume of material in the rack system (Table 4-15 and 4-16), all components were considered to be 0.5 cm thick and all vertical supports as 2 cm wide. With this as a basis, the maximum allowable mold density was determined (Table 4-17) for the same conditions as the continuous process. Using either a boron-aluminum composite or alloy LA141A for the rack system construction, the average allowable densities are 5.5 and 8.5 g/cm^3 for 1.5 and 2 pounds per blade, respectively, for the entire system. Naturally, with the use of a boron-aluminum composite and its high strength, thinner structural members can be used and thus, increase the allowable mold density. The cross-section of the vertical supports in both the racks and compartments are over-designed especially considering a boron-aluminum composite.

As in the continuous process, a materials handling mechanism is necessary to move the mold from the racks to the furnace and to return the molds after processing. With a single chamber furnace only the molds need be handled. A multi-chamber furnace probably would require movement of the removeable compartments to the furnace, and then loading the furnace from the compartment. This would involve slightly more complex equipment.

Table 4-18 gives the volume necessary to house eight total furnace systems using a batch process. The basic assumptions made were (a) the two racks per furnace are 2 m apart allowing room for the materials handling equipment between the racks and (b) the entire system is constructed

TABLE 4-17: ALLOWABLE MOLD DENSITIES FOR BATCH PROCESS

	B-Al	LA141A
Total volume of material for rack system (cm^3)	30.76×10^3	30.76×10^3
Density (g/cm^3)	2.7	1.35
Total weight of material/rack system (g)	83.06×10^3	41.53×10^3
No. of blades/rack	900	900
Wt. of 900 blades @ 200 g	18×10^4	18×10^4
Total mold volume/rack (cm^3)	67.73×10^3	67.73×10^3
Assume max. allowable wt. of 1 lb (454 g) per blade for total system		
Max. allowable wt. (g)	40.86×10^4	40.86×10^4
Allowable wt. for 150 molds (g)	14.55×10^4	18.71×10^4
Allowable mold density (g/cm^3)	2.15	2.75
Assume max. allowable wt. of 1.5 lb (681 g) per blade for total system		
Max. allowable wt. (g)	61.29×10^4	61.29×10^4
Allowable wt. for 150 molds (g)	34.88×10^4	39.14×10^4
Allowable mold density (g/cm^3)	5.15	5.78
Assume max. allowable wt. of 2 lb (908 g) per blade for total system		
Max. allowable wt. (g)	81.72×10^4	81.72×10^4
Allowable wt. for 150 molds (g)	55.41×10^4	59.57×10^4
Allowable mold density (g/cm^3)	8.18	8.8

TABLE 4-18: SPACE REQUIREMENTS IN FACTORY FOR BATCH PROCESS

Item	Design Dimensions	Floor Space (appro.)
1. Rack		
a. width (m)	2.26	2.3
b. depth (m)	0.18	.2
c. height (m)	1.54	1.6
2. Furnaces		
a. width (m)	.75	.8
b. length (m)	.46	.5
c. height (m)	1.20 (.36)	1.25 (.4)
3. Space for materials handling mechanism or space between racks		
a. width		2
b. length (1a) (m)		2.3
c. height (1c) (m)		1.6
4. Space for one furnace system		
width (m) [3a + 2(1b)]		2.4
length (m) [1a + 2b]		2.8
height (m) [1c + 2c]		2.85 (2)
5. Area/furnace system (m^2)		6.72
6. Volume/furnace system (m^3)		19.15 (13.44)
7. Total volume for 8 furnace systems (m^3)		153.2 (107.5)

( ) values for 7.1 in/hr, all other values for 0.5 in/hr in such a manner that four furnaces are back to back. A general layout of the total system is shown in Figure 4-8. Only 153.2 m^3 of space is required for the slow solidification rate and 107.5 m^3 for the fast rate.

Construction of the total system so that four furnaces are back to back should simplify the equipment necessary to obtain the desired solidification rates. These rates may be obtained using either gas cooling or recirculating liquid system. Only two devices (one per furnace group) are then needed instead of eight (one per furnace). This does mean that all process steps for each furnace in a group must operate simultaneously.

The peak power requirements of a batch process will in all likelihood be greater than for the continuous process. However, less total power would be consumed in the batch operation because of the long off times during cooling. It is also possible that the furnaces during each cooling cycle need not be cooled to the temperature of the surrounding environment. This would reduce somewhat the power required in the next heating cycle. Irregardless, an order of 2000 watts per furnace chamber will be necessary. For a single chamber furnace, a total of 16,000 watts would be needed. A five-chamber furnace would require 10,000 watts per furnace or a total of 80,000 watts.

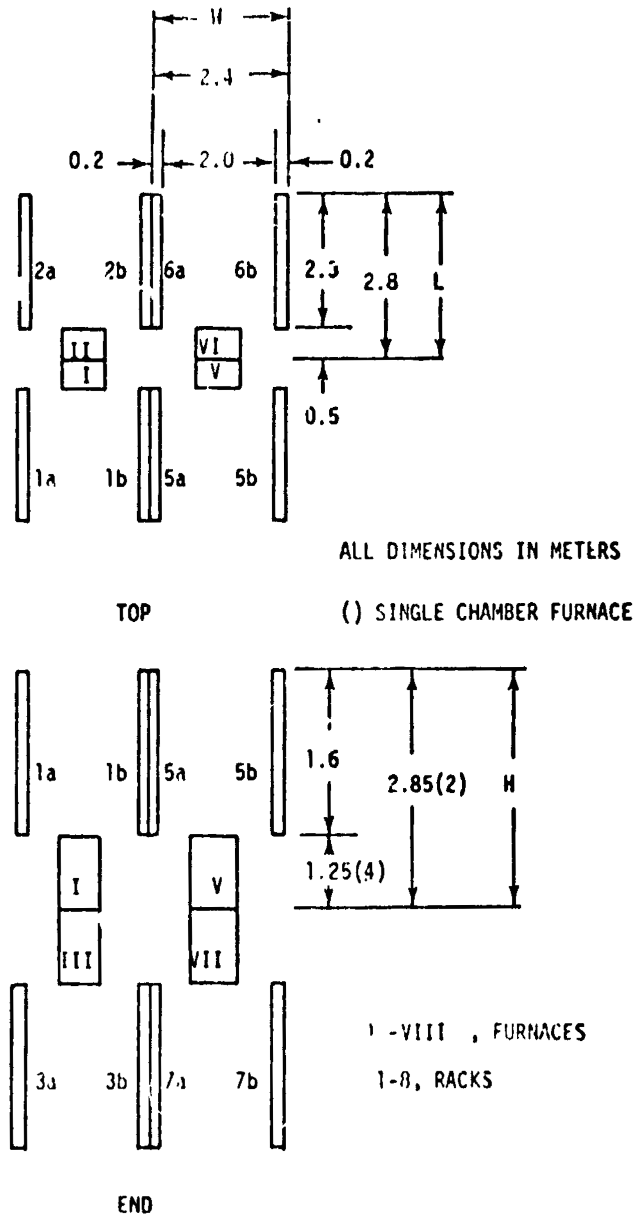


FIGURE 4-8: PROPOSED LAYOUT OF BATCH FURNACE SYSTEMS

4.5 New Technology Required

The economic study of the manufacture of directionally solidified eutectic type turbine blades in space points to the need for the development of new technology in at least three areas. These areas are (a) alloy specifications, (b) mold material and design for re-melting the blades, and (c) furnace design. New technology required in each of these areas is based on the assumption of producing 14,400 blades in approximately 25 days leaving 5 days per month for maintenance and refurbishment. The obvious needs for new technological advances in the above areas are discussed in the following sections.

4.5.1 Alloy Specifications

a. Density of alloy which affects the allowable density of the mold material. This is mainly important during shuttle transportation.

b. Melting point of alloy which affects the selection of mold material to withstand the process temperatures, the power requirements to bring the materials to temperature and the furnace design.

c. Cooling rate required for desired directional solidification microstructure and properties. This greatly affects the number of furnaces necessary, number of blades per mold and the type (size and configuration) of the materials storage system.

4.5.2 Mold Material and Design

a. Development of mold with the following characteristics.

1) fairly light weight (thin-walled but not necessarily low density)

2) high thermal conductivity to reduce time of heating and cooling cycles.

3) high strength to withstand handling during refurbishment and processing.

4) high thermal shock resistance to withstand the rapid heating and cooling cycles.

5) ability to be formed into a two-part mold with a thin-walled complex shape (shell mold type).

6) excellent dimensional stability during blade processing.

7) means of locking mold halves together to minimize flashes or runs and, thus, blade rejection.

8) relatively inexpensive so that mold can be expendable.

9) capable of holding a minimum of three to six blades to reduce the number of furnace systems required.

b. Development of compatible pre-cast blades and molds to produce the necessary dimensional tolerances of the blades during the re-melt process. The thermal expansion and contraction of the blade during melting and solidification and of the mold during the process cycle necessitates excellent control of mold cavity dimensions and the pre-cast blades dimensions. The pre-cast blade must fit into the mold prior to the process and have the correct dimensions afterwards. Technologically, this may be the greatest handicap to overcome for turbine blade processing in space.

4.5.3 Furnace Design

a. Development of means to obtain a constant temperature across a wide furnace chamber to within 2 or 3 degrees to minimize process differences between blades in the same mold. The chamber may vary from 25 to 43 cm wide and be about 7 cm high.

b. Development of quick change heating elements and refractory lining to minimize crew time during maintenance and refurbishment.

c. Development of light weight furnace to minimize launch loads during construction of permanent space factory.

d. Development of cooling system to obtain the desired solidification rates. For a continuous type furnace, this would mean a controlled temperature gradient along the furnace length. For a batch furnace, some means of gas cooling or recirculating liquid cooling system must be provided. The latter could even involve moving the furnace at a controlled rate away from the cooling system and thus reduce the need to greatly cool the furnace during each cooling cycle.

e. For a continuous furnace system, the development of a conveyer system which will maintain the molds in place during passage through the furnace and not thermally distort at the process temperature.

f. Development of an open-end furnace for a continuous system with minimum heat loss to minimize overheating of the space factory.

4.5.4 Other Concerns

Other probable areas of concern involve (a) the development of a strong, light weight frame system or rack for holding the large number of mold during transport and storage and (b) materials handling equipment for moving molds from racks to furnace and return. The final designs of these depend on the number of molds which are storaged and handled. No really new technology is needed for these systems. However, one important area which is outside the scope of this report does need considerable study. This is the advancement in the means of producing large amounts of electrical power in outer-space. Nuclear power generation could be considered for an unmanned permanent space factory where the process is discontinued during maintenance and refurbishment.

4.6 References

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4.7 Appendix A

Dimensions and Volume of Removable Compartments

Overall width of mold seat = mold width + 0.5 cm

Overall depth of mold seat = mold length + 0.5 cm

Inside width of mold seat = overall width - 2 cm

Inside depth of mold seat = overall depth - 2 cm

Vertical distance between seats = mold height + 0.7 cm

Volume of each seat = [(overall width)(overall depth) - (inside width)(inside depth)](thickness)

Total volume of seats = (volume/seat)(9)

Length of vertical supports = height of compartment
= (vertical distance between seats)(8) + thickness of seat (9)

Width of compartment = (width of seat) + (thickness/support)(2)

Depth of compartment = (depth of seat) + (thickness/support)

Total volume of vertical supports = (length)(width)(thickness)(6)

Total volume of material in compartment = total volume of seat + total volume of supports

Maximum load 6 supports can carry = (area)(yield stress)
= (width/support)(thickness/support)(6 supports)(0.155 $\frac{in^2}{cm^2}$ (yield stress)

4.8 Appendix B

Rack Dimensions and Volume

Width of compartment seat = width of compartment + .5 cm

Depth of compartment seat = depth of compartment + .5 cm

Vertical distance between compartment seats = height of compartment + (1.75 cm for the B-Al composite or 1.5 cm for the LA141A alloy)

Volume of each compartment seat (solid) = (width)(depth)(thickness)

Total volume of compartment seats = (volume/seat)(30)

Length of vertical supports = height of rack
= (vertical distance between seats)(5) + (thickness of seats)(6)

Width of rack = (width of compartment seat)(5) + (thickness of supports)(6)

Depth of rack = (depth of compartment seat) + thickness of support

Total volume of vertical supports = (length)(width)(thickness)(18)

Maximum load 18 supports can carry = (area)(yield stress)(width/support) (thickness)(18 supports)(0.155 $\frac{in^2}{cm^2}$

(yield stress)

4.9 Appendix C

Mold Volume and Allowable Density

Surface area of each mold half = surface area of flat mold + (25% blade area)(no blades)
= (mold length)(mold width) + (.25)(blade length)(blade width)(no blades/mold)

Total volume per mold = (surface area)(thickness/mold half)(2 halves)

Total volume of 200 molds = (volume/mold)(200)

Total volume of material in 1 rack and 25 compartments = (total volume/compartment)(25) + volume of 1 rack

Weight of material in 1 rack and 25 compartments = (volume of material)(density of material)

Allowable weight for 200 molds = (maximum allowable weight) - (weight of 600 blades) - (weight of material per rack system)

$$\text{Allowable mold density} = \frac{\text{Allowable weight for 200 molds}}{\text{Volume of 200 molds}}$$

4.10 Appendix D

Diameter Determination of Circular Base for Rack

(From Figure 4-9)

The radius (r) of the circumscribed circle about an equilateral triangle is

$$r = 1/3\, a\sqrt{3} = \frac{a}{\sqrt{3}}$$

where, a is side of triangle or width of rack.

From trigonometric functions in a right triangle

$$b = d \cos 60°$$

$$c = d \sin 60°$$

where, d is the depth of the rack.

Also, from a right triangle

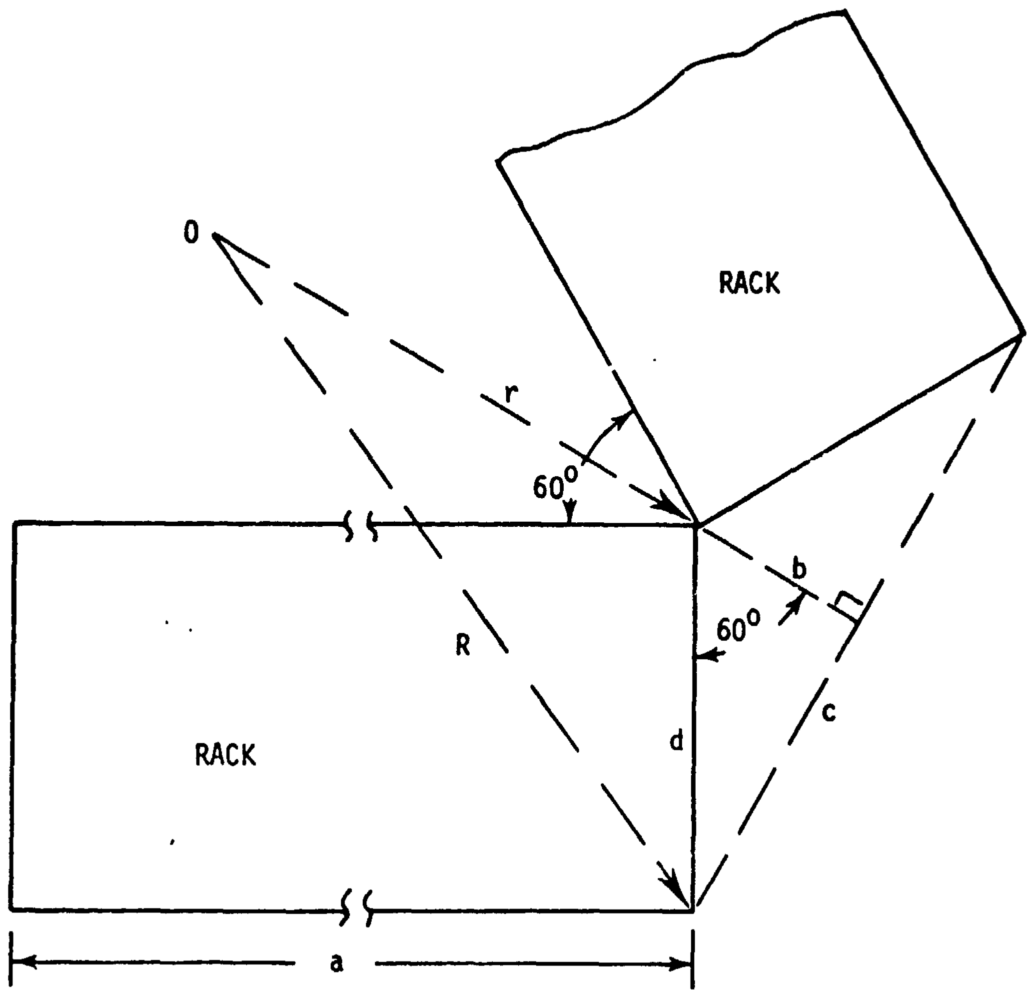
$$R^2 = (r + b)^2 + c^2$$

where, R is the radius of the circular base.

Substituting,

$$R = \sqrt{\frac{a^2}{3} + \frac{ad}{\sqrt{3}} + d^2}$$

Diameter of base, D = 2R



O- CENTER OF CIRCLE WITH RADIUS R AND CENTER OF EQUILATERAL TRIANGLE WITH SIDES EQUAL TO a.

FIGURE 4-9: DIAMETER DETERMINATION OF CIRCULAR BASE FOR RACK.

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5. HIGH PURITY TUNGSTEN TARGETS

5.1 Introduction

X-ray targets were selected as candidates for space processing because of the very high value per X-ray tube. It was felt that any increase in the longevity of X-ray tubes, as a result of space processing, might generate benefits of a sufficiently large magnitude to overcome the costs of space transportation.

The following assumptions were used in the analysis developed on this sector.

a) The manufacture's unit sales price of X-ray tubes was $1,918 in 1974.

b) Tungsten targets were valued at $87 per pound with 1.5 pound target costing $130 in 1974.

c) X-ray tubes have a usable life of 2 years under hospital (or radiological lab conditions and) or 20,000 exposures under conditions of less intense utilization.

d) The rate of growth of the stock of X-ray machines will be constant over the planning period.

e) The rate of growth of the utilization of X-ray machines will be constant over the planning period.

f) Actual U.S. population growth will not differ from Bureau of the Census estimates.

5.2 Description of Tungsten Targets

High purity Tungsten was selected as a material to consider for space processing because Tungsten Targets used in x-ray tubes have several characteristics one or all of which may result in cost saving through space material processing at near zero gravity. First, from an economic standpoint, Tungsten Targets have a high value per pound, and x-ray tubes have a very high value per unit. Tungsten is used in conjunction with an extremely high cost metal, Rhenium, to produce x-ray targets. However, the use of high cost Tungsten-Rhenium alloys could be avoided if the impurities in Tungsten could be removed through low gravity manufacturing techniques. Secondly, an improvement in the quality of x-ray pictures, as a result of improved Tungsten Targets, would produce external benefits; that is, improved pictures would mean less cumulative exposure of individuals to x-rays. Finally, the life of a Tungsten target could be lengthened by processing the metal in a near zero gravity environment.

From a physical and engineering standpoint, Tungsten Targets for x-ray tubes show promise for space manufacturing because of the characteristics of space manufacturing vs. ground manufacturing [1]. Space manufacturing would be expected to increase the purity of the Tungsten used in x-ray targets. This results from the ability to levitate, melt superheat and purify commercial grade Tungsten in a near zero gravity without the use of containers or forming tools [2].

Tungsten or Tungsten Alloy Targets are used in medical arts x-ray tubes; the targets are bombarded with high intensity electrons in order to produce x-rays. An improved Tungsten Target would have higher milliampere ratings and would have smaller focal spots which would result in greater x-ray detail.

An improvement in these operating characteristics of x-ray tubes would result in higher thermal stresses on the Tungsten Targets and will require Tungsten of higher purity.

Tungsten is used in the production of x-ray targets because of its high melting point and high atomic number which allow Tungsten Targets to withstand surface deterioration caused by the high temperatures produced along with the x-rays that are generated. Common causes of x-ray tube replacement are: (a) bearing noise and bearing failure and (b) deposits of Tungsten on the glass envelope of the x-ray tube in the vicinity of the filament.

The powder metallurgy techniques used in the gravity environment production of large Tungsten Targets introduces impurities into the finished target. Furthermore, final stages of target preparation involve the rolling and forging of porous Tungsten at high temperatures, which adds additional impurities to the metal. The impurities will melt and evaporate when the Tungsten Target is put into use. The evaporation of Tungsten impurities may produce a high voltage-puncture of the x-ray tube. The space manufacturing process should be able to eliminate most of the impurities in Tungsten that are inherent in the powder metallurgy techniques presently used to process Tungsten.

Gravity environment techniques of manufacturing Tungsten Targets reduce the ductility of the finished Target as a result of impurities in the form of carbon from dies and or rolls, and atmospheric oxidizing or nitriding. The ductility of the metal is also reduced because of hetrogeneous blending of Tungsten particles. The homogeneity of the mass of blended particles is difficult to maintain using powder metallurgy techniques.

However, in a space environment, materials can be randomly mixed in the absence of gravity. Near zero gravity processing techniques, making use of levitation and forming controls applied while the commercial Tungsten is in a liquid state, should produce Targets of high ductility.

The development of a procedure for producing Tungsten Targets in a near zero gravity environment would allow for the development of high purity targets having a better microstructure than their ground produced counter parts. The advantage space processing would have over ground processing hinges on the use of levitation (under vacuum conditions) to achieve melting of Tungsten without crucibles. This would allow for the consequent purification of Tungsten at melt or at superheating temperatures.

The requirements associated with space processing of High Purity Tungsten x-ray targets are important in three areas [3]. Tungsten Target production in space would be sensitive to the degree of inorbit gravity, the level of contamination, and electromagnetic field. The major process equipment required of a Space Material Processing Facility (SMPF) used in space processing of pure Tungsten Targets involve levitation control equipment, a furnace, local heating equipment; the forming equipment required in space processing includes a large electric power generator, thermal controls, contamination controls, cooling equipment, stabilization controls and pressurization equipment. The SMPF must be automated and the SMPF would use commercial Tungsten as a raw material. Along with the Tungsten Targets, the SMPF would produce gas, heat, and solid waste material which would have to be cleared from the SMPF.

In summary, the SMPF process required to produce pure Tungsten Targets could presumably involve the levitation of commercial grade Tungsten metal without the use of a container. The levitated melt would be zone refined and superheated to drive off impurities. The pure Tungsten would then be solidified while floating in near zero gravity under vacuum conditions.

The commercial grade Tungsten that forms the primary input in this process would first be preprocessed on the ground in the form pressed, sintered bar stock slugs. The Space Material Process Facility referred to earlier would process the slugs into fine grained spheroids of pure Tungsten. The pure Tungsten would then be removed and finally processed into x-ray targets on the ground.

Work done by General Electric Corporation suggests that the pure Tungsten Spheroid produced in space might have a radius of .025 meters and a weight of 1.25 kg. The total time required from melt to the formation of the Tungsten Spheroid, for a batch to be completed in the SMPF, would range from 15 to 50 minutes.

In order to assess the economic potential of Tungsten processing in space an estimate of cost savings resulting from the use of pure Tungsten Targets will be undertaken. This assessment first involves estimating the existing stock of x-ray machines and Tungsten Target components; and then estimating the future demand for replacement of Tungsten Targets during the year study period. Secondly, demand for new x-ray machines and the component x-ray tubes must be estimated over the study period.

5.3 Calculation of the Demand for X-Ray Tube in the United States

In FY 1973, approximately 249,800 medical arts x-ray (dental and medical) machines were in use in the United States [4].In addition, about 6.558 non-medical arts x-ray machines were in operation in U.S. laboratories.

However, this study is limited only to the demand for Tungsten Targets used in x-ray tubes employed in the medical arts in the United States. In the recent past the number of dental and medical x-ray units have increased at an annual rate of about 5 percent. This growth rate is expected to extend into the future. The non-medical arts x-ray machines in service have increased at a rate of about 22 percent per year. However, non-medical arts x-ray equipment was not included in this analysis. These figures, along with population estimates (See Table 5-1), will be used to calculate the growth in demand for x-ray units over the twenty year study period (Table 5-2). The replacement demand for antiquated x-ray equipment and the net growth in new demand for x-ray equipment is shown in Table 5-4.

In order to determine the demand for x-ray tubes, it is necessary to know how intensively the x-ray machines will be used each year of the planning period. The number of new and replacement x-ray tubes are a function of the stock of x-ray machines in use each year and the number of exposures (or pictures taken) per x-ray tube. Table 5-2 shows the projected number of exposures for x-ray tubes during the planning period. It is assumed in this paper that the life of an x-ray rube will average 2 years or 20,000 exposures.

The intensity of use of x-ray tubes depends to a large degree on whether the x-ray machines are used for dental or medical purposes [5]. Survey results for 1961, 1964, and 1970 show that the rate of use of dental x-rays per 100 persons in the United States increased rapidly over the 9 year period. It appears that 33.8 persons out of every 100 non-institutionalized persons had dental x-rays made in 1970. Persons between 15-29 make the greatest use of x-ray services and the use of dental x-ray treatment

TABLE 5-1: TOTAL POPULATION: UNITED STATES, 1970 to 2000
(Total population including Armed Forces overseas)

Year (July 1)	Series C	Series D	Series E*	Series F
Estimates (thous.):				
1970	204,879	204,879	204,879	204,879
1973	210,4C4	210,404	210,404	210,404
Projections (thous.):				
1975	215,872	215,324	213,925	213,378
1980	230,955	228,676	224,132	221,848
1985	248,711	243,935	235,701	230,913
1990	266,238	258,692	246,639	239,084
1995	282,766	272,211	256,015	245,591
2000	300,406	285,969	264,430	250,686
Percent Increase:				
1973-1975	2.6	2.3	1.7	1.4
1975-1980	7.0	6.2	4.8	4.0
1980-1985	7.7	6.7	5.2	4.1
1985-1990	7.0	6.0	4.6	3.5
1990-1995	6.2	5.2	3.8	2.7
1995-2000	6.2	5.1	3.3	2.1
Percent Increase since 1973:				
1975	2.6	2.3	1.7	1.4
1980	9.8	8.7	6.5	5.4
1985	18.2	15.9	12.0	9.7
1990	26.5	23.0	17.2	13.6
1995	34.4	29.4	21.7	16.7
2000	42.8	35.9	25.7	19.1

Source: U.S. Bureau of the Census, Current Population Reports, "Estimates of the Population of the United States, by Age and Sex: April 1, 1970 to July 1, 1972," Series P-25, No. 490; and ibid., "Projections of the Population of the United States, by Age and Sex: 1972 to 2020," Series P-25, No. 493; and ibid., "Estimates of the Population of the United States to August 1, 1973," Series P-25, No. 506.

*Note: Series E was used for the population projections relating to the demand for Tungsten Targets

TABLE 5-2: ESTIMATES OF THE NUMBER OF X-RAY EXPOSURES AND X-RAY MACHINES IN USE IN THE UNITED STATES FROM 1975 TO THE END OF THE PLANNING PERIOD 1991

	U.S. Population (1000)[1]	Dental X-Ray Visits per 100 persons[2]	Dental X-Ray Visits (1000)[2]	Medical X-Ray Visits per 100 persons [2]	Medical X-Ray Visits (1000)[2]
1975	213,925	39.8	85,142	60.9	130,280
1976	215,787	41.0	88,473	61.9	133,280
1977	217,745	42.2	91,888	62.9	136,962
1978	219,794	43.4	95,391	63.9	140,448
1979	221,926	44.6	98,979	64.9	144,030
1980	224,132	45.8	102,663	65.9	147,703
1981	226,399	47.0	106,408	66.9	151,461
1982	228,709	48.2	110,238	67.9	155,293
1983	231,044	49.4	114,136	68.9	159,189
1984	233,381	50 6	118,091	69.9	163,133
1985	235,701	51.8	122,093	70.9	167,112
1986	237,989	53.0	126,134	71.9	171,114
1987	240,235	54.2	130,207	72.9	175,131
1988	242,429	55.4	134,306	73.9	179,155
1989	244,566	56.6	138,424	74.9	183,180
1990	246,639	57.8	142,557	75.9	187,199
1991	248,645	59.0	146,701	76.9	191,208

	Dental X-Ray Machines (1000)[3]	Medical X-Ray Machines (1000)[3]	Total X-Ray Machines (1000)[3]	Dental X-Ray Visits per machine	Medical X-Ray Visits per machine
1975	148	128	276	575	1016
1976	158	132	291	558	1010
1977	169	137	306	542	1003
1978	181	141	322	527	997
1979	193	145	339	513	990
1980	206	150	356	499	981
1981	219	154	373	485	975
1982	234	160	394	472	968
1983	249	165	415	458	962
1984	265	170	435	445	955
1985	283	176	459	432	948
1986	301	182	483	419	941
1987	320	187	507	407	933
1988	341	193	534	394	1693
1989	362	199	561	382	916
1990	385	206	591	370	907
1991	409	212	621	359	898

	Dental X-Ray Exposures Per Visit	Medical X-Ray Exposures Per Visit	Dental X-Ray Exposure per machine	Medical X-Ray Exposure per machine
1975	4.02	1.3	2,312	1,321
1976	4.00	1.3	2,232	1,313
1977	3.98	1.3	2,157	1,304
1978	3.96	1.3	2,087	1,296
1979	3.95	1.3	2,026	1,287
1980	3.93	1.3	1,961	1,275
1981	3.91	1.3	1,896	1,264
1982	3.90	1.3	1,841	1,258
1983	3.88	1.3	1,777	1,251
1984	3.86	1.3	1,718	1,242
1985	3.85	1.3	1,663	1,232
1986	3.83	1.3	1,605	1,223
1987	3.81	1.3	1,551	1,213
1988	3.79	1.3	1,493	1,201
1989	3.78	1.3	[illegible]	1,191
1990	3.76	1.3	1,391	1,179
1991	3.74	1.3	1,343	1,167

NOTES:

Totals may not equal to the sum of subcategories because of rounding.
[1]Based on U.S. Bureau of Census, Current Population Reports, Series P-25, No. 506.
[2]Based on U.S. Department of Health, Education, and Welfare, Bureau of Radiological Health, Population Exposure To X-Rays: U.S. 1970, November 1973.
[3]Based on U.S. Department of Health, Education, and Welfare, Bureau of Radiological Health, Report of State and Local Radiological Health Programs, July 1974.

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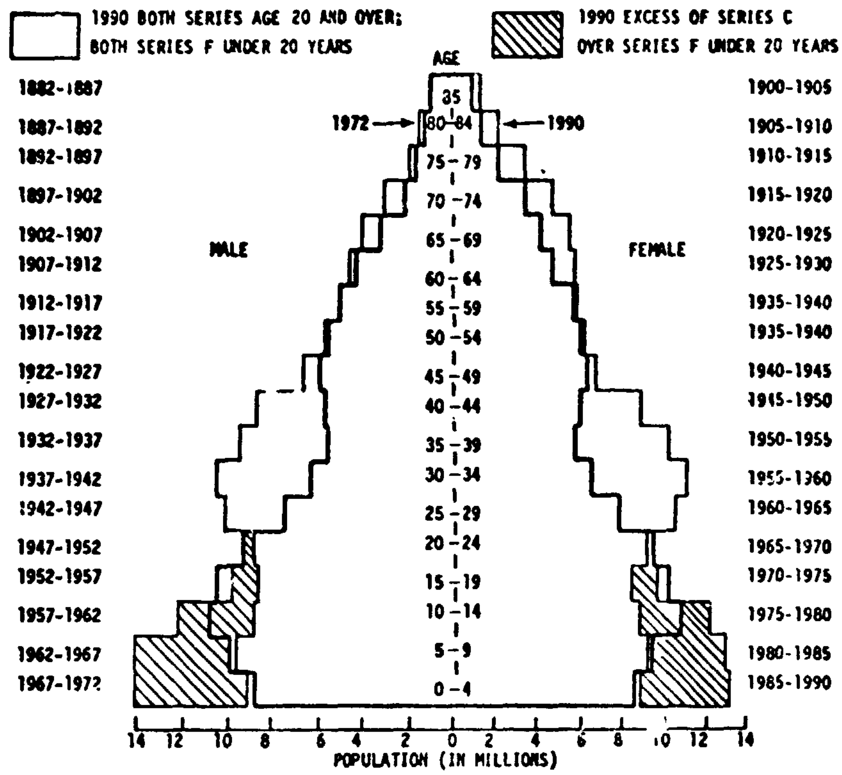
increases rapidly with income. In contrast, it appears that the medical x-ray rate is largely independent of income.

Sample survey data for 1961, 1964, 1970 suggests that persons make more medical x-ray visits than dental x-ray visits. In 1970, it was estimated that the rate of use of medical x-rays per 100 persons was 55.9. However, fewer exposures are taken per medical visit than in the case of dental visits. Again, as income increases, the frequency of use of medical arts (dental and medical) x-rays increases. This suggests that rising real incomes, as well as greater social emphasis and individual attention to personal health, will result in the continued rapid growth of x-ray use by the United States population. We might expect conservatively to see real income increase by 2 percent per annum over the study period. This kind of real income increase would be associated with a median family income of $14,986 in 1990 as opposed to $10,281 in 1971 (See Table 5-3).

It should be noted here that the rate of usage of x-ray services by the United States population increases in the case of medical x-rays up to the age of 60. However, the rate of usage of dental x-rays declines after persons reach their early 20's in the United States. Figure 5-1 suggests that the 1990 age distribution will continue to support the growing demand for dental x-rays associated with increases in real income. For purposes of this analysis, it was assumed that the rate of dental x-rays per 100 persons would increase by 1.0 percent per annum. The respective rates would be 39.8 and 60.9 per 100 population in 1975 and would grow to 54.2 and 72.9 per 100 in 1987.

The demand for Tungsten Targets for medical arts x-ray tubes used in the United States depends on the number of new x-ray machines put into



Source: U.S. Bureau of the Census, Current Population Reports, "Estimates of the Population of the United States, by Age and Sex: April 1, 1970 to July 1, 1972," Series P-25, No. 490; ibid., "Projections of the Population of the United States, by Age and Sex: 1972 to 2020," Series P-25, No. 49?; and Census Bureau Records.

FIGURE 5-1: POPULATION BY AGE AND SEX: UNITED STATES, 1972 AND 1990

TABLE 5-3: NUMBER AND PERCENT DISTRIBUTION OF FAMILIES BY MONEY INCOME FOR 1971 WITH PROJECTIONS FOR 1975, 1980, 1985, and 1990 IN CONSTANT 1971 DOLLARS BY SELECTED ANNUAL COMPOUND GROWTH RATES

Money Income Intervals	Base Year 1971	1975 Growth Rates 2.0	3.0	4.0	1980 Growth Rates 2.0	3.0	4.0	1985 Growth Rates 2.0	3.0	4.0	1990 Growth Rates 2.0	3.0	4.0
Total families (mil.)	3.3	56.2	56.2	56.2	61.3	61.3	61.3	66.3	66.3	66.3	70.5	70.5	70.5
Percent Distribution	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Under $4,000	13.0	11.7	11.0	10.3	10.0	8.6	7.4	8.2	6.6	5.1	6.9	4.9	3.5
$4,000 to $9,999	35.2	32.4	30.6	29.2	28.7	25.5	22.5	24.9	20.8	17.5	21.3	16.9	12.9
$10,000 to $14,999	26.9	26.7	26.9	26.4	26.4	24.8	23.0	24.6	20.5	17.4	21.9	16.9	13.4
$15,000 to $24,999	19.5	22.5	23.9	25.5	26.1	29.3	31.5	30.1	33.6	33.8	32.9	33.7	30.1
$25,000 and over	5.3	6.8	7.6	8.6	8.9	11.9	15.6	12.2	18.5	26.3	17.1	27.7	40.1
Median income (dol.)	10,281	11,012	11,468	11,878	12,069	13,259	14,385	13,476	15,481	17,713	14,986	18,122	21,778
Mean income (dol.)	11,583	12,463	12,960	13,470	13,673	14,928	16,284	15,138	17,354	19,868	16,856	20,289	24,378

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service each year and upon the replacement demand for x-ray tubes. The demand for new x-ray machines along with additional descriptive data is presented in Table 5-2. This estimating procedure was straight forward. The existing stock of medical arts x-ray machines for 1970 and 1973, was used to develop annual growth rates for dental and medical x-ray machines. The growth rate was 3.2 percent for medical x-ray machines and 5.2 percent for all medical arts x-ray machines. These calculations suggest that by 1980, the beginning year of the program, there will be 206,000 dental x-ray machines in use in hospitals and private offices in the United States. Table 5-4 shows the annual growth increments for new dental and medical x-ray machines in the United States. The estimated growth increment is 17,604 for 1980 and 30,746 in 1991.

The demand for replacement tubes is more difficult to calculate. The following procedures were used to make the replacement calculations shown in Table 5-4. It was assumed that an average x-ray tube would require replacement after 2 years of operation or 20,000 exposures; tubes using very large x-ray targets would need replacement after 10,000 exposures. Intensive use of x-ray equipment in hospitals or radiological examination facilities would likely result in tube replacement in about 24 months. However, the infrequent use of x-ray equipment in private medical offices, results in much longer tube life. In 1980, using the population and x-ray usage rates, as well as the x-ray machine stocks given in Table 5-2, it appears that less than 2,000 dental exposures and less than 1,300 medical exposures will be taken per machine year. This suggests tube life of ten years or more. This latter figure seems most improbably. An independent estimate of the number of x-ray tube replacements was made based on

TABLE 5-4: ANNUAL DEMAND FOR TUNGSTEN TARGETS ARRISING FROM THE USE OF NEW X-RAY MACHINES AND THE REPLACEMENT OF OLD X-RAY TUBES IN THE UNITED STATES FROM 1976 TO THE END OF THE PLANNING PERIOD IN 1991

	New X-Ray Machines (Units)[1]	X-Ray Tube Replacement (Units)[2]	Total Tubes Required (Units)	Value X-Ray Tubes ($1000)[3]	Discounted Value X-Ray Tubes (5%-$1000)[4]
1976	14,373	13,667	28,040	53,781	
1977	15,121	14,377	29,498	56,577	
1978	15,907	15,125	31,032	59,519	
1979	16,734	15,912	32,646	62,615	
1980	17,604	16,739	34,343	65,869	62,707
1981	18,520	17,609	36,129	69,295	62,850
1982	19,482	18,525	38,007	72,897	62,983
1983	20,496	19,488	39,984	76,689	63,115
1984	21,562	20,502	42,064	80,679	63,171
1985	22,682	21,568	44,250	84,871	63,314
1986	23,862	22,689	46,551	89,285	63,482
1987	25,103	23,869	48,972	93,928	63,589
1988	26,408	25,110	51,518	98,811	63,733
1989	27,782	26,416	54,193	103,951	63,826
1990	29,082	27,783	56,865	109,067	63,804
1991	30,746	29,228	59,974	115,030	64,071

	Discounted Value X-Ray Tubes (10%-$1000)[4]	Discounted Value X-Ray Rubes (15%-$1000)[4]	Value of Tungsten Targets ($1000)[5]	Discounted Value Tungsten Targets (5%-$1000)[6]
1976			3,645	
1977			3,834	
1978			4,034	
1979			4,244	
1980	59,875	57,240	4,464	4,250
1981	57,238	52,387	4,697	4,260
1982	54,746	47,820	4,941	4,269
1983	52,378	43,866	5,198	4,278
1984	50,102	40,097	5,431	4,291
1985	47,867	36,664	5,752	4,291
1986	45,803	33,571	6,052	4,303
1987	43,770	30,714	6,366	4,310
1988	41,896	28,062	6,697	4,319
1989	40,021	25,676	7,0[illegible]	4,326
1990	38,173	23,340	7,392	4,324
1991	36,579	21,511	7,797	4,343

	Discounted Value Tungsten Targets (10%-$1000)[6]	Discounted Value Tungsten Targets (15%-$1000)[6]
1976		
1977		
1978		
1979		
1980	4,058	3,879
1981	3,680	3,551
1982	3,711	3,246
1983	3,550	2,973
1984	3,404	2,724
1985	3,244	2,485
1986	3,105	2,276
1987	2,967	2,082
1988	2,840	1,902
1989	2,713	1,740
1990	2,587	1,589
1991	2,487	1,458

NOTES:

Totals may not equal to the sum of subcatagories because of rounding.
[1]Based on estimates found in Table 5-2.
[2]Based on sales information found in Current Industry Reports, Series MA-36N.
[3]Uses an estimated 1974 manufactures sales value of $1,918 per x-ray tube.
[4]Assume that all benefits accrue at the end of the year.
[5]Uses an estimated 1974 Tungsten Target value to the manufacturing of $130 per target.
[6]Assume that all benefits accrue at the end of the year.

electronics data published in the Current Industry Reports [6].

The following estimating procedure was used. In 1968, the Current Industry Reports showed $13,577,000 million in individual sales of x-ray tubes. Assuming an average manufacturer's sales price of $1,572 per tube, an estimated 8,637 x-ray tubes were sold individually in 1968. These individual sales are assumed to constitute the replacement demand for x-ray tubes. The "replacement tube-medical arts machine" ratio is approximately .047. This ratio was applied to the stock of x-ray machines in use each year to obtain the x-ray tube replacement demand shown in Table 5-4. An estimated 16,739 replacement tubes would be required in 1980, the beginning year of the program. The demand for replacement tubes was expected to reach 29,228 units by 1991.

The total demand for x-ray tubes for new machines and replacement purposes amounts to an estimated 34,343 units in 1980 and 39,974 units at the termination of the program in 1991. At current (1974) manufacturer's prices, assumed to a little under $2,000 per tube, this constitutes an expenditure of about 120 million dollars (1974 dollars) by 1991. At present, it is assumed that 1.5 pound x-ray target would cost approximately $130. The total target component cost of x-ray tubes in 1991 would be about $7.8 million dollars.

It would appear from this that space processing of Tungsten Targets, to be successful, could not depend primarily on cost cutting by substituting Tungsten for Rhenium. Space processing, to be successful, would have to extend the life of the target and x-ray tube greatly beyond to two year intensive use life of x-ray tubes. A considerable increase in tube life would be required as the transportation costs associated with the Space

Shuttle operations exceed the existing earth production costs of Tungsten Targets. If continued experimentation shows that the quality and life of x-ray targets and ultimately x-ray tubes can be greatly increased by manufacturing the target in a zero gravity environment so that ground manufacturing plus replacement cost savings exceeds the space transportation costs allocated to the processing activity then the process could be more seriously considered as a candidate for space materials processing. Using a 10 percent discount rate and assuming 984 flights in the program, we would have an operating cost of $162 per pound of Tungsten and a capital amortization cost of $95 per pound. If all costs operating and amortization were covered, it would appear that the space transportation costs (not considering space processing costs) alone would amount to $257 per pound of Tungsten. At present, if it is assumed that 1.5 pound Tungsten Target costs $130 the processed material has a manufactured cost of $87 per pound. Given these assumptions, an approximate three-fold increase in target life would be required to cover space transportation costs. In addition to the transportation costs, the cost of the SMPF would have to be allocated to the space processed Tungsten.

On the other hand, if the only cause of x-ray tube replacement was the failure of the Tungsten Target, a doubling of tube life would amount to a cost savings of a little under $2,000 (manufacturer's price) per unit. If this assumption could be reasonably made, it would appear that Tungsten Targets would constitute a reasonable candidate for space manufacturing. For purposes of this study it assumed that the average life of an x-ray tube was 5 years with a standard deviation of 1.5 years.

Table 5-4 shows the total value of x-ray tubes in 1974 manufacturer's prices for the study period. It was assumed that the unit price in 1974 was $1,918. The current annual manufacturer's sales values of x-ray tubes were then discounted at 5 percent, 10 percent, and 15 percent. The total sales values for the planning period are $1,060,372,000, $760,645,000, $568,448,000, $440,948,000 for 0, 5, 10, and 15 percent discount rates. A doubling of tube life would result in cost saving of $220,474,000 for manufacturer's sales discounted at 15 percent. A 15 percent discount would seem appropriate in that we are dealing with cost savings in the private sector and a 15 percent rate of return in this sector would seem to be in line with the rate of return expected by a new manufacturing operation.

Table 5-4 also shows the manufacturer's value of Tungsten Targets. The Targets are assumed to be worth $130 per unit in 1974. All annual Target values for Targets are presented in 1974 dollars over the planning period.

The Tungsten Target values are discounted at 5, 10, and 15 percent. The resulting discounted total values for the entire planning period are $71,883,000, $51,564,000, $38,546,000, $29,905,000 for 0, 5, 10, and 15 percent discount rates respectively. A doubling of the life of the targets alone would produce a cost savings of $14,953,000, assuming a 15 percent rate of discount.

5.4 Summary and Conclusions

In summary, it must be stated that the preceeding analysis represents only a rough estimate of benefits based on very crude data. However, the analysis is indicative of the benefits that may be expected in the area of space processing of Tungsten Targets given the assumption of a doubling of the life of x-ray tubes. It must be emphasized that the benefits accruing to this production process appear primarily to depend on the space materials processing activity to lengthen the life of the x-ray Targets and also of x-ray tubes. The exact improvement of the life expectancy of the x-ray tubes depends upon the results of experimental processing of Tungsten Targets in a zero gravity environment. However, at retail values that average around $2,950, per x-ray tube there is little doubt that an improvement in the life of the tube has the possibility of considerable cost saving, saving sufficiently high to warrant the continued consideration of Tungsten Targets as a candidate for space processing.

Furthermore, it must be realized that it is highly probable that the costs of space transportation will be at least as high as the estimates presented in an earlier section of this report, however, the probability of the benefits being received over the primary period is not as high. To begin with, the benefits are based on continued growth in demand for radiological health services at the rate experienced in the recent past. There is a high probability that these rates may not be sustained over the entire planning period. It is difficult to sustain high growth rates over long periods of time. In short, we cannot be as certain that the level of benefits will be achieved as we are that the level of cost will be incurred. Finally, no account has been taken of the cost of a SMPF for the refining of Tungsten and the production of Tungsten X-ray Targets. The costs of this facility would have to be excluded from the benefits of the space process.

5.5 References

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2. R. T. Frost (study manager), "Electromagnetic Containerless Processing Requirements and Recommended Facility Concept and Capabilities for Space Lab," General Electric, Contract NAS 8-29680, Final Report, 13 May 1974, pp. 3-15/16; and H. L. Bloom (study manager), "Study for Identification of Beneficial Uses of Space (Phase I), "General Electric, Contract NAS 8-28179, Final Report, Volumn II, Book 2 Technical Report, Results, Conclusions and Recommendations, April 23, 1973, p. III-257/258.

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6. ELECTROPHORESIS OF BIOLOGICAL MATERIALS

6.1 Introduction

The objective of this study was to obtain information concerning the selection of a biological product or products to be manufactured in the near zero gravity of space. The effect of gravity on terresterial manufacturing of biological products limits the extent to which certain products can be produced especially in the area of purification. Utilization of near zero gravity may enhance the purification of these products. Also the accomplishment of space processing of certain biological products which have not been produced on earth would be of great benefit to mankind.

6.2 Candidate Electrophoresis Processes and Products for Space

6.2.1 Electrophoresis Methods

Manufacturing procedures for space were restricted to those that utilized the process of electrophoresis. Electrophoresis is the separation of a mixture of particles into various fractions by placing the mixture in or on the proper media and passing an electrical current through the media. The separation is dependent on the difference in charges of the various particles causing them to migrate at different rates. Some of the problems of electrophoresis are due to the effect of gravity which: a) reduces the movement of the particles, b) causes a sedimentation of larger particles (especially cells). Preliminary results on two previous space flights by NASA indicates that the near zero gravity of space can be utilized to improve the separation of particles by electrophoresis [1, 2, 3].

One method of separation of mixtures of substances is continuous deflection electrophoresis or free flow electrophoresis. This method appears to be one of the best for separation of large quantities of material. The process with the highest probability of success is one developed by K. Hanning [4] and is based on the vertical free flow of fluid to minimize the gravitational influence. The problem with this system is when the pH of the solvent approaches the pK of the particle being separated, flocculation occurs. Gravity then becomes a problem because the flocculated particles settle before separation occurs. The use of this method in zero gravity would allow for separation of the particles closer to the isoelectric pH (as the pH approaches the pK of a given particle the net charge of the particle approaches zero, this lowers its electrophoretic mobility). Separation of the flocculated particles would be based on their charges and mobility. This would allow for separation at a pH equal to the pK of one of the samples. By using this method, flocculated protein would have a greatly different mobility from non-flocculated protein and this would enhance the separation.

The capacity of the suggested method (on earth) is about five to ten grams per day when using heavy filter paper. This capacity probably would be much greater in space because filter paper would not be used and thereby removing any adsorption effect that may complicate or slow separation. Researchers have two different opinions as to the effect of gravity on this apparatus. One is that no further advantages are to be gained by removing the effects of gravity and the other is that the removal of gravitational effects would improve resolution, especially in relation to large protein and cells.

A second method that may be used is isoelectric focusing [5, 6, 7]. The basic theory behind isoelectric focusing involves the properties of carrier ampholytes and the behavior of protein in a natural pH gradient created by electrolysis of a mixture of ampholytes. A natural pH gradient is always positive from the anode to the cathode, that is, the pH gradient always increases monotonically in the direction of the current. Isoelectric focusing can be considered to be simultaneous focusing of the two classes of ampholytes. One low molecular weight class (carrier ampholyte) and one high molecular weight class (protein). Protein is assumed to have no buffering capacity or conductivity in the apparatus. With the assumption of a constant pH gradient and constant field strength, the protein peptide will migrate at a steady speed. The resolution powers of the system is based on the mobility and isoelectric point of the particles being separated.

A third process that could be used is isotachophoresis [8]. The principle of isotachophoresis is the passage of a constant direct current through a vessel containing a buffering ion, thus, causing the sample ions to move at different speeds. The ions will continue to move until they have separated in the order of their mobility. The sample ions to be fractionated are inserted between two homogenous buffer zones formed by the leading ion and the terminal ion. This brackets the electrophoretic mobility of all the sample ions; with the mobility of the leading ion being higher and the terminal ion being slower. When the electrical current is applied, the migrating ions can move only as fast as the one in front of it. As the mobility of the sample and the terminal ion is lowered, the field in each compartment adjusts itself to assume equal voltage. In the course of migration the sample ions are separated into their compartments and arranged in order of their decreasing mobility.

6.2.2 Products and Application

Candidates for biological products for space processing and the applications of these products are contained in Table 6-1 and discussed below.

a. The natural resistance to infections and toxicity is almost totally a result of the action of immunoglobulins and gamma globulins. The absence of these globulins result in a decreased resistance to several types of diseases in general called agammaglobulinemia (Table 6-2). The injection of pure sub-fractions of I_gG into suitable animals will in turn develop specific antibodies in the immunoglobulin. The antibodies will then be separated from the animal serum and used for diagnostic purposes. In diagnostic use, the presence of immunoglobulin is indicated if a reaction occurs on mixing a blood sample (from a patient) with the antibodies.

b. The pancreas contains beta cells that produce insulin. A pure culture of beta cells may be implanted into patients suffering from diabetes if proper cell matching can be accomplished. The major problem with separation on earth is the purity of the cultures. An estimated eight to twelve million diagnosed and undiagnosed Americans suffer from diabetes. More than two hundred thousand Americans will suffer diabetes related death each year then will die of cancer. The problem with insulin therapy is some patients develop an immunologic response to insulin and it becomes ineffective.

c. The bone marrow contains many types of cells. One type of particular interest is the stem (undifferentiated) cell that has the ability to differentiate into erythrocytes and/o 'anulocyted. A

TABLE 6-1: CANDIDATE FOR SPACE PROCESSING

Desired Product	Material (Starting)	Procedure	Method: Earth	Method: Space	Applications and Remarks
a. Pure samples of I_gG's subclasses 1, 2, 3, 4	Pure I_gG_3 or serum	Separate I_gG into its four subclasses	(only partially)	Electrophoresis (fluid) isoelectricfocusing	Production of monospecific antibody for diagnosis of immunoglobulin disease - 1 gm. of each would produce sufficient amount of antisera to supply U.S. for one year.
b. Pure cultures of Beta cells	Isolated Islet of langerhans from Pancreas	Separation of Beta cells from Islet of langerhans	not done efficiently	Electrophoresis (fluid)	Transplantation (into pancreas to correct diabetes) - 10-12 million diabetics in U.S.- Problem of transplant rejection.
c. Pure cultures of stem cells without compliment fixing cells	Bone marrow	Separation of bone marrow stem cells	not done efficiently	Electrophoresis (fluid)	Basis research, transplantation in patient with neoplasia of bone marrow - Problem of transplant rejection.
d. Pure cultures of tumor cells	Tumor cell culture	Separation of tumor cells	not done efficiently	Electrophoresis	Basic research (to allow exact studies to be made on tumor membrances). (It is believed that the membrane of the tumor is the key to the cure).
e. Urokinase producing cell	Tissue culture (Kidney cell)	Separation of kidney cell	not done efficiently	Electrophoresis	Treat conditions where breakdown of clotts are required.
f. Pure samples of antihemophilic factors	Cryoprecipitate	Separate antihemophilic factors	Cryoprecipitate	Electrophoresis	Treatment of hemophilia
g. Pure cultures of B & T cells	A column separated culture	Separation of Lymphocytes (B & T)	Column with a glasswool packing	Electrophoresis	Immature lymphocytes are educated against tumor cells. (T cells have the capacity to inhibit growth of tumor cells). Basic research (tumor rejection).

TABLE 6-2: AGAMMAGLOBULINEMIA DISORDERS

Type of Disorders	Treatment	Complications
Congenital Agammaglobulinemia	controlled by antimicrobial chemotherapy	Untreated; chronic brochiectasis manifestation; two years of age in the form of pneumonia, sepsis meningitis, and followed by death
Dysgammaglobulinemia		an estimated 1 in 200 random admissions have some form of this disease
Primary Acquired Agammaglobulinemia	nonspecific	Sprue syndrome diarrhes, steatorrhea and in some instances modular lympoid hyperplasia. This group of patients have an unusually high incidence of autoimmune diseases (pernicious anemia, hemolytic anemia)

tremendous amount of basic research could be performed if a pure culture of the stem cells could be obtained. Also these cells could be transplanted into a person suffering from neoplasia of the bone marrow. The major problem is that earth methods of separation are not sensitive enough to separate pure cultures of cells. This same problem is present in several of the following processes involving the separation of cells.

d. Separation of tumor cells would allow more exact studies to be made on tumor membranes which is believed to be the key to tumor regression. Tumor cells have a higher surfact charge than normal cells. Partial separation has been achieved on earth. The present methods do not allow for complete separation on earth.

e. The separation of a kidney cell culture into pure sub-fractions; one of which produces urokinase. Urokinase would have medical benefits in the treatment of embolism (blood clots). This enzyme activates plasminogen to plasmin (which is present in the blood), which then dissolves blood clots. Interest in this area has already progressed to the extent that a preliminary experiment will be attempted in space in 1976.

f. The purified antihemophilic factors would be used to maintain the clotting ability in patients suffering from this genetic disease. The process of obtaining these factors is by cryoprecipitation (fractional freezing). This method requires a large volume of blood with a low yield and the end product is not pure, which can produce allergic reactions or hepatitis.

g. In many cancer patients the circulating lymphocytes are T cells which have the capacity to inhibit growth of tumor cells. It is thought that many cancer patients posses T cells but also have a factor which inhibits or blocks the effect of the T cells. The proposed procedure would be to isolate the immature lymphocytes and educate them (by exposure to mature cells resistant to the inhibiting factor) and inject them into patients possessing tumors; thereby, inducing rejection of the tumor. This would have a far reaching effect in basic immunologic research and probably reduce the amount of time in developing a cure for cancer.

6.3 Selection of Candidate for Analysis

6.3.1 Criteria for Selection

The selection of a candidate was based on the economical return and the ease of handling the materials. The immunoglobulin (I_gG) subclasses are protein molecules and can be handled much easier than cell cultures. Cell cultures are difficult to maintain since they require special growth media and handling procedures. The media must be changed frequently in order to maintain a viable culture. The subclasses of IgG are protein molecules and require no special attention after separation. Also small quantities of the four subclasses that are pure (1 gm of each subclass) would be sufficient to produce mono-specific antibodies to supply the United States for one year. If space processing of the subclasses is successful the cost involved would be justified by the far reaching effects connected with the use of pure subclasses.

6.3.2 Discussion of Selected Candidate

The antibodies produced by the body are the first line of defense against infection and invasion from foreign material. Seventy-five to eighty-five percent of the serum antibodies are contained in the IgG class of gamma globulins. The relative ratios of each subclass are 70:18:8:4 for IgG_1, IgG_2, IgG_3, and IgG_4 respectively. These antibodies are made up of two short polypeptides and two long polypeptides connected by disulfide (-s-s-) bonds. The major difference in the antibodies are the location of these bonds and the vatiable end of the large peptide. The location (-s-s.) changes their three dimensional configuration thereby changing their antigen specificity.

The reason for separating these immunoglobulin into subclasses is for the production of monospecific antibodies. These antibodies will be used for the diagnosis of agammaglobulinemia. Certain antibodies are restricted to specific functions; for example, the antibodies for carbohydrates are predominantly IgG_2, anti-isohemagglutins are mostly IgG_1 and the Rh antibodies are IgG_1 and IgG_3. A variety of disorders exist with deficiencies in one or more classes of these immunoglobulins. Subclass imbalance has also been noted in non-sex-linked hypogammaglobulinemia, in which patients have a marked depression of IgG titer. IgG catabolism is increased in myotonic dystrophy (a dominant genetic disease) and in autoimmune disorders.

6.3.3 Processing of Candidate

a. Preparation on Earth

The preparation for space processing would be to obtain 100 grams of commercial IgG or human serum may be used and can be obtained from any blood bank.

b. Processing in Space

In space, the commercial IgG would be separated into its four subclasses by electrophoresis. The method of electrophoresis employed could be one of the three discussed in Section 6.2.1.

c. Processing on Earth after Space Processing

The processing on earth of the pure sub classes of the IgG would involve injection of each into ... le animals (goats). The animal would produce antibodies s... of ... of subclass it received. Serum or plasma from these a... wo... obtained and the diagnostic reagents made from serum.

6.4 Advantages of Space Processing

There are approximately 7,000 hospitals in the United States and about 2,000 of these perform diagnostic tests for agammaglobulinemia. The benefits of space processing of commercial IgG depend upon the extent of the improvement of diagnostic tests resulting from the use of space processed serum, and the number of tests performed. Estimates of the number of tests performed in the United States vary considerably; however, a large referral medical school--The Birmingham University Hospital--ran 557 such tests in 1973. If the Birmingham University Hospital were an average institution, this would suggest that the 2,000 hospitals operating in the U.S. performed 1,144,000 tests in 1973. This would seem to be the upper limit of an estimate of the range of the tests performed.

A 1973 sample survey of persons and organizations using electrophoresis suggested that the respondents on the average performed 40 tests per month or 450 tests per year. Applying this average to the 2,000 U.S. hospitals, we might expect about 960,000 tests to be run per year. A lower limit to the range of tests performed in the U.S. is perhaps 700,000 tests per year as suggested by some industry sources.

This report assumes that 960,000 tests were performed in 1973. Estimates of the U.S. population for 1973 indicate 210,404,000 persons were living in the U.S. at that time. This suggests that a test was performed on one out of every 219 persons in the U.S. in 1973. This rate was used to project demand for the diagnostic tests over the planning period. (See Table 6-3).

If the relationship between agammaglobulinemia tests and population for the U.S. remains unchanged over the planning period 1,023,434 and 1,135,365 tests are projected for 1980 and 1991 respectively. The corresponding hospital costs of these tests, in 1973 dollars would be $12,281,000 and $13,624,000 for the beginning and terminal years of the 12 year planning period used in this analysis. The total (not discounted) cost of the projected tests would be about $215,290,000. This would represent the 17,940,848 expected tests that are forecast for the period 1980-1991. The total cost to the patients during this period would be considerably greater assuming an estimated hospital charge of about $17.50 for a total immunoglobin test. These costs would probably be incurred with or without space processing.

To reinterate, the primary advantage of space processing of immuglobulin material into four subclasses is to produce mono-specific antibodies. Approximately 75 to 85 per cent of serum antibodies are contained in the IgG class of gamma globulins. Space processing would probably require sortie flights of an orbiter for the purpose of separation of the commercial IgG into its four subclasses by electrophoresis. All additional processing could be done in a gravity environment. The levels of demand for serum projected in this study suggests that one flight per year over the 12 year planning period would be sufficient to supply the demand for serum.

The 17,940,848 IgG tests projected for the 12 year planning period would be more effective in diagnosing agammaglobulinemia as a result of the use of space processed serum. The cost resulting from the gain in medical diagnostic

Date	U.S. Population (1000)[1]	Number of IgG Tests[2]	Diagnostic Test Cost ($1000)[3]	Diagnostic Test Cost Discounted at 5% ($1000)[3]	Diagnostic Test Cost Discounted at 10% ($1000)[3]	Diagnostic Test Cost Discounted at 15% ($1000)[3]
1975	213,925	976,826	11,722			
1976	215,767	985,329	11,824			
1977	217,745	994,269	11,931			
1978	219,794	1,003,626	12,044			
1979	221,926	1,013,361	12,160			
1980	224,132	1,023,434	12,261	11,696	11,165	10,679
1981	226,539	1,033,787	12,405	11,252	10,252	9,380
1982	228,709	1,044,333	12,532	10,826	9,415	8,240
1983	231,044	1,054,995	12,660	10,415	8,647	7,258
1984	233,381	1,065,667	12,788	10,020	7,861	6,358
1985	235,701	1,076,260	12,915	9,637	7,218	5,584
1986	237,989	1,086,708	13,040	9,267	6,692	4,902
1987	240,235	1,096,963	13,164	8,910	6,141	4,353
1988	242,429	1,106,982	13,284	8,563	5,634	3,776
1989	244,566	1,116,740	13,401	8,227	5,167	3,313
1990	246,639	1,126,205	13,514	7,901	4,737	2,905
1991	248,645	1,135,365	13,624	7,586	4,341	2,546
12 YEAR TOTAL		17,950,844	155,608	114,300	87,210	69,224

Date	Marginal Cost of One Flight Discounted at 0% ($1000)[4]	Marginal Cost of One Flight Discounted at 5% ($1000)[4]	Marginal Cost of One Flight Discounted at 10% ($1000)[4]	Marginal Cost of One Flight Discounted at 15% ($1000)[4]
1975				
1976				
1977				
1978				
1979				
1980	7,022	4,906	3,726	3,345
1981	7,022	4,906	3,726	3,345
1982	7,022	4,906	3,726	3,345
1983	7,022	4,906	3,726	3,345
1984	7,022	4,906	3,726	3,345
1985	7,022	4,906	3,726	3,345
1986	7,022	4,906	3,726	3,345
1987	7,022	4,906	3,726	3,345
1988	7,022	4,906	3,726	3,345
1989	7,022	4,906	3,726	3,345
1990	7,022	4,906	3,726	3,345
1991	7,022	4,906	3,726	3,345
12 YEAR TOTAL	84,264	58,872	44,712	40,146

Notes:

[1] Based on U.S. Bureau of Census Current Population Reports, Series P-25, No. 506.
[2] Based on industry estimates.
[3] Represents ground production costs based on a diagnostic test cost of $12.
[4] Represents the marginal or incremental cost of one shuttle flight per year using various interest rates for a level of activity of 82 flights per year over the 12 year planning period.

TABLE 6-3: ESTIMATES OF THE NUMBER AND COST OF IMMUNOGLOBULIN TEST IN UNITED STATES HOSPITALS FROM 1975 TO THE END OF THE 12 YEAR PLANNING PERIOD IN 1991 efficiency would be one shuttle run of the orbiter per year. The marginal cost of one additional flight, assuming a discount rate, ranges between $7.87 to $7.02 million depending on the total number of flights undertaken. No provision is being made here for the special equipment required for electrophoresis processing or for the possibility of shared flight costs.

Using the lower limit of this range, the total cost of the additional orbiter shuttle flight required to perform the initial zero gravity environment electrophoresis would be about $4.70 per test. In current dollars this cost increment is 39 percent of the hospital cost of a complete IgG test. It is possible that the increased efficiency in diagnosing agammaglobulinemia type illnesses would warrant the estimated $16.70 cost of the "new" test. It should be noted that if the marginal cost of the 12 flights and the earth processing cost were discounted at 5 percent the average total cost per diagnostic test, including space processing, would be approximately $9.65. The costs figures presented in Table 6-3 are based on the assumption that the entire cargo space of the orbiter is required to perform the electrophoresis processes. If this is not the case, a shared flight with some other space processing activity would greatly reduce the cost of producing the serum. The benefits associated with the more efficient diagnostic test would probably involve a reduced number of vists to the doctor's office by the patient and the more rapid diagnosis of a wide range of diseases.

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7. CRYSTAL STUDY AND ECONOMETRIC MODEL

Note: Work on the crystal sutdy and the econometric analysis of crystals was terminated at the request of NASA project directors. A much more in depth study has been funded with another agency to deal specifically with this problem. This project was directed to concentrate its efforts on the turbine blade portion of the study, and work continues in that area. The present report represents a statement of the work done in the crystals area with the econometric model and describes the plans that were laid for completion of efforts in this area.

7.1 Introduction

The purpose of this section is to develop an econometric model that can be used to predict demand and supply figures for crystals over a time horizon roughly concurrent with that of NASA's Space Shuttle Program - that is, 1975 through 1990. Also included in the model is an equation to predict the impact on investment in the crystal-growing industry.

Actually, two models are presented. The first is a theoretical model which follows rather strictly the standard theoretical economic concepts involved in supply and demand analysis. However, severe data limitations far prevented a comprehensive testing of this model. Consequently a modified version of the model was developed which, though not quite as theoretically sound, was testable utilizing existing data sources

7.2 Approach to the Study

To facilitate an understanding of the methodology employed, this section outlines the plan devised for completion of the study. A flow diagram is given in Figure 7-1. The first step in the study was to construct the theoretical econometric model, following established econometric procedures for supply and demand analysis. Upon completing the model, a broad based search for data was made to determine if the econometric model could be tested statistically. Since all of the data was not obtainable, the model had to be revised to give a testable model. The model was then tested.

The sparcity of adequate data in the areas necessary resulted in an inordinate amount of time being spent on research. Several of the sources used for data are not well known or widely utilized. All data sources are listed separately in the bibliography. Some data sources had relatively recent beginnings, resulting in information that was not usable due to the lack of information in earlier years.

After the model testing had been completed, the next planned step was to predict crystal demand for high value crystals by using individual product lines in the model. Data collection proceeded along these lines and some information on the relationship of crystal use in these product lines was established. Data collection attempts were not successful in all of the desired product lines.

After predicting crystal demand, estimates of potential crystal revenues were to be made by estimating a potential price structure for crystals. Some current prices were located but it had become apparent to the researchers that more direct contact with the crystal manufacturers was necessary to obtain information. Mail efforts to obtain price lists failed as firms refused to send this information.

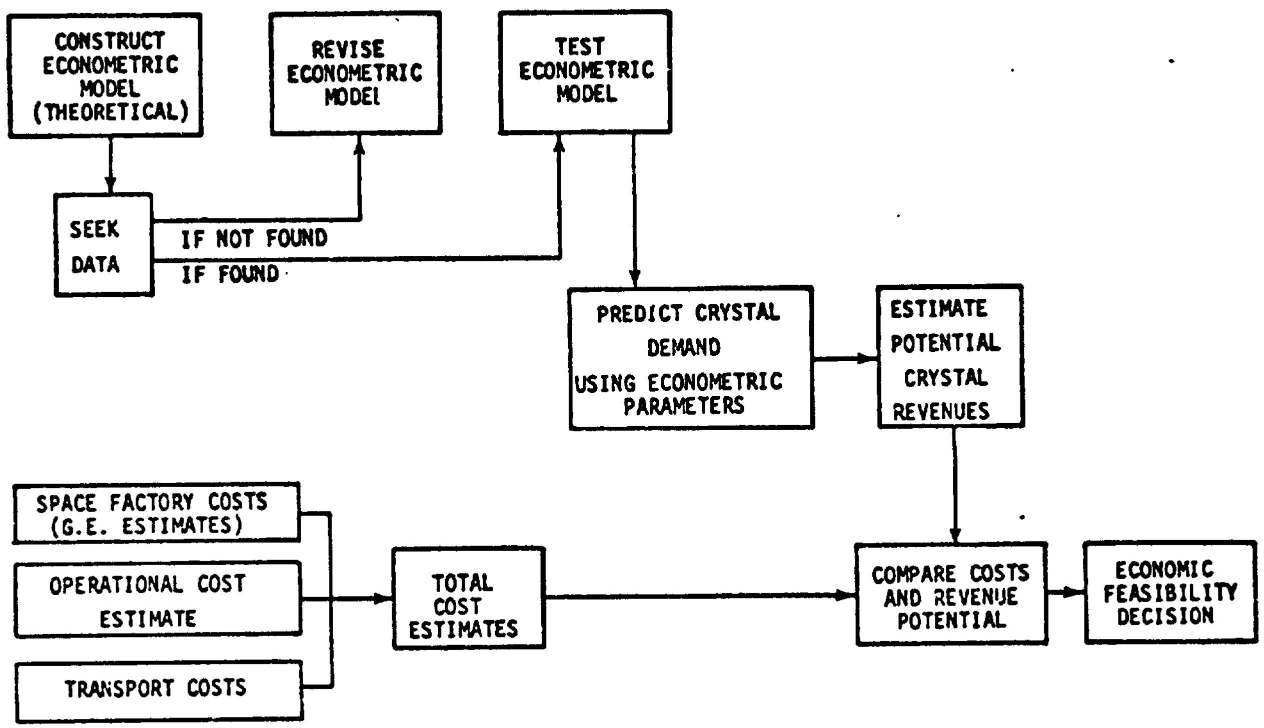

FIGURE 7-1: APPROACH TO STUDY

From a cost standpoint, efforts were made to estimate total cost of production figures through combining separate estimates of a) Factory costs, utilizing estimates made by G.E., b) Transportation costs, with weight factors considered, and c) Operational cost estimates. Work was not done on item c. Finally, costs and revenues are compared to yield an economic feasibility decision.

7.3 Theoretical Model as Applied to Crystal Study

The theoretical model is presented in Table 7-1. It reflects the fact that crystals are used primarily as intermediate products in electronics, and as such, their demand is basically a "derived demand." That is, the demand for crystals is derived from the demand for the final products that use crystals as inputs. Table 7-2 lists numerous products that utilize crystals. Some of these are already being commercially produced, while others have been proposed on the basis of the anticipated high-quality crystals that space processing could yield. Any attempt to calculate the demand for crystals as an intermediate product should, theoretically, include a calculation of the demand for each of these final products.[1] Table 7-3 shows some of the crystals that are of interest for space processing possibilities and their area of use.

The primary determinants of demand are generally portrayed in economic texts as a) tastes of the buyer, b) income of the buyers, c) the prices of substitutes and complements for the product. The determinant

[1]Actually, many of the applications listed in table 7-3 as final products are themselves also intermediate products, and thus the list could be broken down even further. However, it is felt that the listing in Table 7-3 is more than sufficient to provide a basis for calculating the demand for crystals.

TABLE 7-1: THE THEORETICAL MODEL

EQUATIONS

$$DF = a_0PFP + b_0GNP + c_0FGSE + d_0EEX + u_0 \tag{1}$$

$$DC = a_1DF + b_1PCU + c_1PC + u_1 \tag{2}$$

$$SC = a_2PC + b_2PX + u_2 \tag{3}$$

$$DC = SC \tag{4}$$

$$IC = a_3DC + b_3CUC + u_3 \tag{5}$$

DF = the demand for final products that utilize crystals as an input, expressed as a quantity.

PFP = the prices of the various final products

GNP = real Gross National Product (U.S.)

FGSE = Federal Government expenditures on electronics

EEX = electronics exports by the U.S.

DC = the demand for crystals, expressed as a quantity

PCU = the proportion of crystal use as an input, relative to total inputs

PC = the prices of the crystals

SC = the quantity of crystals supplied

PX = the prices of the factors of production used in crystal processing

IC = investment in the crystal processing industry

CUC = capacity utilization in the crystal industry

TABLE 7-2: APPLICATIONS OF CRYSTAL USE [1]

1. Computer Memories

   a.) magnetic bubbles
   b.) holographic
   c.) page composer
   d.) surface wave acoustic delay lines
   e.) magnetic beam addressable

2. Optoelectronics

   a.) light-emitting diodes (LED's) and LED displays
   b.) lasers
   c.) ferroelectric graphic displays

3. Optical Communications Systems (fiber Optics)

   a.) inter-city transmissions
   b.) inter-office trunks
   c.) interconnections of communications equipment

4. Pyroelectric Sensors For Use In:

   a.) earth resources surveying
   b.) pollution monitoring
   c.) thermal imaging for medical diagnosis
   d.) fire location
   e.) infrared astronomy

5. Surface Wave Acoustics

   a.) switchable correlators used in integrated communications, navigation, and identification systems
   b.) simple correlators used in light-weight radar systems
   c.) large time-bank-width delay lines for use in electronic warfare and radar systems
   d.) parallel processors employing long, complex transmission paths

6. Ultrasonics

TABLE 7-3: CRYSTALS OF INTEREST AND AREAS OF USE* [1]

Crystal	Area of Use
Aluminum Gallium Arsenide	2a
Aluminum Nitride	5, 1d
Barium Sodium Niobate	4, 3, 1b
Bismuth Germanate	5, 1d
Bismuth Tantalate	1c, 1b
Bismuth Titanate	2c, 1b
Gadolinium Iron Garnet Films	1e
Gadolinium Molybdate	1c
Gallium Arsenide	2b
Gallium Nitride	2a
Gallium Phosphide	2a
Indium Aluminum Phosphide	2a
Indium Gallium Phosphide	2a
Lead Germanate	3
Lead Tin Telluride	2b
Lithium Germanate	1d
Lithium Iodate	3
Lithium Niobate	5, 1d, 1b
Lithium Tantalate	6, 1d, 1b
Potassium Iodate	3
Potassium Lithium Niobate	3
Rare Earth Gallium Garnet Substrate	1a
Rare Earth Iron Garnets or Rare Earth Gallium Iron Garnet Films	1a
Ruby (Nd^{3+})	2b
Sapphire	5
Sodium Iodate	3
Spinel	5, 1d
Triglycine Sulfate	4
Yttrium Aluminum Garnet	2b, 1d
Yttrium Iron Garnet	2b, 1e, 1d

*Areas of Use from Table 7-2

of a specific quantity demanded of the product is the price of the product itself. Most models dealing with demand analysis include a demand equation that utilizes the variables with the exception of the price of substitutes and complements. These are sometimes handled as special cases but for our purposes, crystal demand, substitutability and complementarity are probably not major considerations.

Equation (1) thus specifies variables that reflect the basic approach to demand. The demand for the final (crystal using) product, (DF) is a function of a) the price of the final product (PFP), b) income as reflected by gross national product (GNP), c) Federal Government Spending on Electronics (FGSE), and d) Electronics Exports (EEX). The last two variables serve as a proxy for tastes because the majority of the products involved are heavily electronic in nature. Many of the crystal-using products listed in Table 7-2 are purchased in large quantites by the Government. And in some instances - for example, with large time - band - width delay lines for use in electronic warfare and radar systems - the Government may in fact be the only consumer of a product. For this reason, annual Federal Government expenditures for electronics is included in Equation 1. Finally, in recognition of the fact that the electronics industry is highly international in scope, the level of electronics exports by the United States is included in Equation 1.

As mentioned above, the demand for crystals, as an intermediate good, is derived largely from the demand for the final products. This is reflected in Equation 2, in which the demand for the final products (DF) is included as an explanatory variable of the demand for crystals (DC). Equation 2 also includes the proportion of crystal use (PCU) relative to total inputs, and the price of the crystals (PC). Just knowing the demand for the final products is not enough; it is also necessary to know the proportion of the value of output attributable to crystal inputs; i.e., the proportion of crystal value to total product value. And, just as the price of the final good will have an impact on the demand for the final good, so the price of the intermediate good will have an impact on the demand for the intermediate good, so that the price of crystals (PC) must be included in Equation 2.

Equation 3 represents the supply equation. The primary determinants of supply are the costs of the inputs the producer must bear and the level of technology in production. Similarly to demand the determinant of a spcific quantity supplied is the price of the product. A producer determines his production level largely on the basis of profit considerations. Profits arise whenever total revenue - which is equal to the price of the good times the quantity sold - is greater than total cost - which is equal to the prices of the factors of production times the quantity of the factors necessary to produce the output. Equation 3 - the supply equation - reflects this relationship. The supply of crystals (SC) is a function of the prices of the crystals (PC) and the prices of the factors of production used in crystal processing (PX).

Equation 4 defines the equilibrium conditions of the model. The equilibrium position will be achieved where the quantity of crystals supplied - whether through Earth processing, space processing, or both - is equal to the quantity of crystals demanded. A statement of equilibrium in the market place is a necessity because of the definitions accorded to Demand and Supply in the economic literature.[1]

Equation 5, the Investment equation is somewhat disjointed from the model in that most supply-demand econometric models do not include such an equation. However, a relationship does exist between the level of demand for crystals and the level of investment in the industry. Equation 5 will allow some prediability regarding this investment impact or the economy.

Investment in the crystal industry (IC) is a function of the demand for the industry's product (DC), and the utilization of existing plant capacity in the industry (CUC). If there is an expanding level of demand for crystals, then crystal processing firms will be more apt to increase their investment expenditures because of expected future profits. On the other hand, a declining demand for crystals will lead to a cutback in investment expenditures for capital goods used to produce crystals. Another factor determining the level of investment in an industry is the extent to which the industry is employing the capacity that it already has. If an industry has idle capital equipment, then it will be less likely to invest in new capital, even in the face of expanding demand. Instead, the idle plant equipment will be activated. On the other hand, in an industry that is operating close to capacity, an expanding demand will be more likely to induce an increase in new investment.

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[1]Demand is defined as a schedule of all the quantities of a good or service that consumers are willing and able to buy at various prices and at a specified time and place. Supply is defined as a schedule of all the quantities of a good or service that producers are willing and able to sell at various prices and at a specified time and place. Once price is established in the market the amount bought equals the amount sold, hence supply equals demand at some equilibrium price and quantity.

An exception to this general rule is the case of a new or innovative product. If there is an expanding demand for such a product, and the existing capital equipment of the industry cannot be used to produce it, then competitive pressures may force the firms in this industry to invest in new capital equipment, whether they have idle capacity or not. Space processing could lead to the creation of many new and innovative high-technology crystal-using products. If a large number of such goods evolve from space processing, this will result in new investment expenditures regardless of the level of capacity utilization of conventional plant and equipment in the crystal-processing industry.

In the testing of an econometric model, relationships are found that are based on historical data. When data cannot be found, substitution by proxy variables can sometimes by utilized. At other times modification of the model may be necessary. In the case at hand, a thorough search of the literature in government publications and technical journals failed to reveal any data regarding the quantities of crystals sold in this country. Furthermore, replys to our survey mailed to crystal manufacturers showed a strong reluctance on their part to disclose price and volume information to the researchers.[1]

The absence of quantity data forced a substantial modification of the model to enable testing procedures. Changes have been kept to a minimum and every effort has been made to maintain a theoretical consistency with the original model. Other problems were in locating data on specific prices and costs of production in certain strategic crystal using product lines.

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[1]The results of the survey are summarized elsewhere in this report.

7.4 The Testable Model

To facilitate ease of testing, the decision was made to cor truct a model and test the model for its statistical significance utilizing data that could be easily obtained and would yet provide relevant insights for the study at hand. Consequently the aggregated electronics industry was chosen. The view taken is that once the applicability of the model for one industry has been shown, it can be applied to the individual product lines somewhat more freely.[1] The modified version of the model is shown in Table 7-4. The model is couched in terms of the electronics industry since that is how it was tested. Planned testing would have centered upon product lines that are heavy crystal users, notably computers, lasers, and light emitting diodes.

The model has been modified along the following lines. Quantity demanded has been replaced by total revenue as the dependent variable in the demand equation, equation (6), TRE represents the total revenue in the electronics industry. Rather than a simple quantity variable, the TRE variable is a price times quantity for all elements included within the industry. The best data [2] available for this is given by the Standard Industrial Classification Code (SIC) 36 - "Electrical Equipment and Supplies." The value of industry shipments for SIC 36 is used to denote or proxy demand.

In equation 6, one other modification was made. Instead of directly employing a price variable, a price index for the electronics industry

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[1]This approach also allowed continued search time for data on individual product lines.

TABLE 7-4: MODIFIED ECONOMETRIC MODEL

$TRE = a_0 + b_0 PE_i + c_0 GNP + d_0 FGSE + e_0 EEX + u_0$	(6)
$DE_q = TRE / PE_i$	(6a)
$SE_d = a_1 + b_1 PE_i + c_1 COM + u_1$	(7)
$SE_q = SE_d / PE_i$	(7a)
$IE = a_2 + b_2 TRE + c_2 CUE + u_2$	(8)
$DE_q = SE_q$	(9)
$TRC = TRF \times PCV$	(10)
$TRC_t = \Sigma TRC_p$	(10a)

TRE = total revenue for the electronics industry (SIC 36)

PE_i = an index of prices for electrical equipment and supplies (SIC 36)

GNP = real Gross National Product (U.S.)

FGSE = Federal Government expenditures on electronics

EEX = U.S. exports of electronics (SIC 36)

DE_q = a quantum figure for demand of electronics

SE_d = the supply of electronics, in dollar terms (SIC 36)

COM = the cost of materials for the electronics industry (SIC 36)

SE_q = a quantum figure for the supply of electronics

IE = investment in new electronics capital (SIC 36)

CUE = capacity utilization in the electronics industry (SIC 36)

TRC_p = total revenue attributable to crystals in use in a particular product line

TRF = total revenue from the sale of a particular product line that utilizes crystals as an input

PCV = the proportion of crystal value as an input of a particular product line relative to total inputs

TRC_t = the sum of the total revenues for the crystals used in all of the particular product lines in question was used. This is necessary because we are dealing not with one product with one price structure, but with an entire spectrum of products with widely divergent prices. Total revenue is equal to price times quantity. Normally to find quantity, it is only necessary to divide total revenue by the price of the product. Not so in this instance. Division of TRE by PE does not yield an average quantity for any product, rather an average "quantum" which is basically just a pure number. Of itself the quantum has no meaning. However, by comparing different quantum over different years an index of the relative volume of output in the industry is obtained that is somewhat more informative. In Equation 6a total revenue is divided by the price index (PE_i) to yield such a "quantum" figure (DE_q). This quantum figure is an alternative measure to total revenue - one that can be projected to provide another view of future electronics demand.

A similar modification is made to equation 3 to yield equation 7, the supply equation. Since quantities supplied are not known a dollar valuation must be utilized. The supply of electronics in dollar terms (SE_d) is a function of the price index for SIC 36 and the cost of materials used in SIC 36. The value of industry shipments will be used to represent this dollar supply. The cost of materials will be used as a proxy for the prices of the factors of production because data for this latter variable is not available. This should provide a reasonable substitute. To arrive at a quantum figure for supply (SE_q), the dollar value of supply (SE_d) will be divided by the price index (PE_i), as in Equation 7a.

In the theoretical model, the investment equation - Equation 4 - is designed to predict levels of capital expenditures in the crystal industry. Again the scarcity of data on the crystal industry makes this impossible. Therefore, Equation 8, the modified investment equation, will be used to project investment levels for the electronics industry as a whole. Some insight into investment in the crystal industry can then be inferred from this information. However, the interpretation here will not be quite as adaptable as for the supply and demand equations. With the supply and demand equations, the projected approach would be along individual product lines. With the investment equation, restrictions limit the further breakdown of investment level to product lines. Hence, the best estimate would be to assure that the relationship of investment to revenues and capacities in electronics industry as a whole is the same as the relationship of investment to revenues and capacities in the crystal industry. Such as estimate is fraught with pitfalls, but would probably be a reasonable "ball park" figure.

In equation 7, investment in the electronics industry is a function of the demand for that industry's products (TRE) and the current level of capacity utilization in the industry (CUE). Capacity utilization is not published explicity for SIC 36. Adequate data do exist that allow development of a relatively good measure of capacity utilization. This technique was developed by Klein and Preston [3]. The technique involves the calculation of peaks in man-hour utilization by an industry, with the peaks designated as full capacity. A trend line is then fitted to these points to represent "potential capacity." The percent to which the level of man-hours at any particular time is less than or greater than the corresponding point on this line provides a measure that will be used as a proxy for capacity utilization. For example, if a peak point on the trend line connecting peaks is 100,000 man-hours in time period t, and actual manhours were 80,000, capacity utilization would be estimated as 80% of full capacity.

Equation 9 again represents an equilibrium position. But now, it is the "quantum" of demand that will be equal to the "quantum" of supply at equilibrium. At this point, the model would be complete if the end goal were to estimate the demand and/or supply of electronics (or individual final product lines). To arrive at the demand and supply for crystals one added step is necessary, provided by equation 10.

The proportion of crystal use (PCU) is included in Equation 2 of the original model as an explanatory variable of the quantity of crystals demanded. In Equation 10, the proportion of crystal "value" (PCV) to provide an estimate of the dollar demand (TR) is multiplied by the total revenue of the individual product line for crystals. Equation 10 is an identity in which the total revenue for crystals is a percentage of the total revenue for the final products. This percentage is the PCV - the portion of the total revenue of a product attributable to its crystal inputs.

To arrive at a figure for the demand for crystals, the total revenue of the final products using crystals (TRF) must first be determined. These products are those that have been identified as potential users of space-grown exotic crystals in Table 7-2. The sales figures for each of these products will then be multiplied by its PCV, yielding the total revenue of crystals associated with the particular final product (TRC_p).

Summing all of these individual figures will provide a measure of potential total revenue for crystals. This final result (TRC_p) is given by equation 10a.

7.5 Testing and Estimating Procedure

A schematic outline of the testing and estimating procedure is shown in Figure 7-2. Input is of three types: historical data, projected data, and estimates of the proportion of crystal value in each product line tested. Historical data is inserted in the dependent and independent variables in the testable model. By applying statistical regression techniques of ordinary least squares (OLS), a set of econometric parameters are measured which show the relationship of the independent to the dependent variables.[1] Regression on the data for the Electronic industry then would provide a reasonable check on the model's general applicability. The next step would be to do the same for individual product lines. This would yield the econometric parameters for projection purposes.

The projection of the data involves the linear projection of the independent variables data. This projection is accomplished by assuming a linear projection of the data and applying OLS regression again with each variable regressed against a time trend variable. The assumption of linearity is a simplification that could be relaxed if for any reason, researchers felt the future held change. For example, a good possibility would be that linear projection of real gross natural product are high as a result of energy and raw material shortages in the next few years.

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[1]The ideal testing technique for a simultaneous equation model is two or three stage least squares; (2SLS) or (3SLS). However, the small number of observations results in very limited degrees of freedom when this technique is used. Frequently the results are very similar to ordinary least squares (OLS). The model is tested by both methods. Projections, however, were made using only OLS.

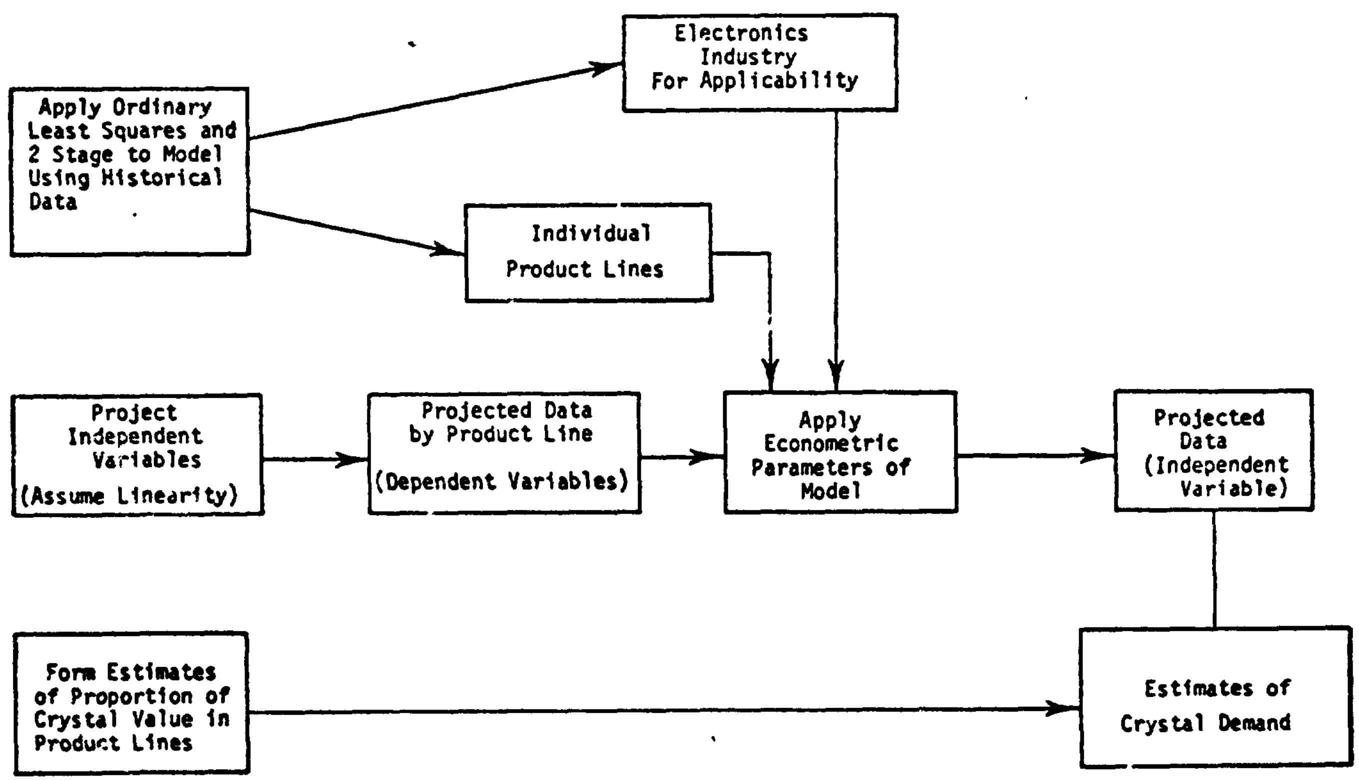

FIGURE 7-2: TESTING AND ESTIMATING PROCEDURE

The linearity of the independent variables forces linearity on the dependent variable even when calculated with the econometric parameters. However, a versatility is introduced that is superior to simple linear projection for this model when any of the linearity assumptions for the independent variables are dropped. Applying the econometric parameters from the historical data to the projected data give projections for the dependent variables, supply and demand as proxied in the model.

Combining the dependent data projections with estimates of the proportion of output value would then yield estimates of future crystal demand in dollars.

7.6 Results of the Tests on the Electronics Industry

The original data for the electronics industry are given in Table 7-5 and Table 7-6. Table 7-5 gives the data for the Supply Equation and Table 7-6 the data for the Demand Equation. GNP (Table 7-6) is given in constant 1958 dollars, i.e., the inflationary impact has been removed to give a more realistic measure of actual increases in physical output.

Table 7-7 gives the projections of the independent variables in the demand equation for 1975 to 1991. The simple linear regression (OLS) technique was applied. The results for each independent variable is given at the top of the page, equations (a) through (d). These data are employed in Table 7-8. Applying the coefficients obtained from the regression analysis, prediction of total revenue in electronics (TRE) 1975-1991 are shown. This is converted into a quantum to give a relative measure of physical volume.

Table 7-9 gives the supply equation projections. The coefficients applied are shown in the equation at the top of the page. The projected data for

TABLE 7-5: HISTORICAL DATA ON SUPPLY EQUATION VARIABLES

(millions)

Year	VALUE IND. SHIP.[4]	*PE_i[5]	COM [4]	TREND
1961	24,592.2	99.2	10,983.7	1
1962	27,589.1	99.2	12,310.7	2
1963	29,840.2	98.0	12,942.6	3
1964	30,784.7	98.0	13,324.0	4
1965	35,127.3	98.2	15,430.7	5
1966	40,842.6	100.3	18,472.6	6
1967	43,361.0	104.0	19,437.3	7
1968	46,470.4	108.1	20,321.6	8
1969	48,913.7	112.4	21,115.9	9
1970	48,420.8	117.4	21,003.7	10
1971	49,168.1	122.1	20,923.0	11

*PE_i is in index form, with 1958 = 100

TABLE 7-6: HISTORICAL DATA ON DEMAND EQUATION VARIABLES

(millions)

Year	VALUE IND. SHIP. [4]	*PE_i [5]	GNP [5] (constant $-1958)	FGSE [6]	EEX [7]
1958	19,588.2	100.0	447,300	4,540	1,026.3
1959	21,131.4	101.2	475,900	5,934	977.7
1960	22,796.2	100.6	487,700	5,239	1,033.8
1961	24,592.2	99.2	497,200	7,560	1,147.7
1962	27,589.1	99.2	529,800	9,905	1,280.1
1963	29,840.2	98.0	551,000	9,516	1,366.4
1964	30,784.7	98.0	581,100	9,844	1,511.4
1965	35,127.3	98.2	617,800	9,200	1,569.2
1966	40,842.6	100.3	658,100	9,810	1,821.5
1967	43,361.0	104.0	675,200	10,932	2,028.3
1968	46,470.4	108.1	706,600	10,659	2,256.0
1969	48,913.7	112.4	725,600	10,712	2,710.7
1970	48,420.8	117.4	722,500	11,171	2,971.9
1971	49,168.1	122.1	745,400	11,774	2.967.4

*PE_i is in index form, with 1958 = 100

TABLE 7-7: PROJECTIONS OF DEMAND EQUATION INDEPENDENT VARIABLES

(a.) $PE_i = 93.23 + 1.462(TREND)$

(b.) $GNP = 412{,}110 + 25{,}408.088(TREND)$

(c.) $FGSE = 5{,}618.6 + 443.61(TREND)$

(d.) $EEX = 522.72 + 165.24(TREND)$

Year	TREND	(a.) PE_i	(b.) GNP**	(c.) FGSE**	(d.) EEX**
1975	18	119.546	869,455.57	13,603.58	3,497.04
1976	19	121.008	894,864.06	14,047.19	3,662.28
1977	20	122.470	920,272.14	14,490.80	3,827.52
1978	21	123.932	945,680.22	14,934.41	3,992.76
1979	22	125.394	971,088.30	15,378.02	4,158.00
1980	23	126.856	996,496.38	15,821.63	4,323.24
1981	24	128.318	1,021,904.40	16,265.24	4,488.48
1982	25	129.780	1,047,312.40	16,708.85	4,653.72
1983	26	131.242	1,072,720.40	17,152.46	4,818.96
1984	27	132.704	1,098,128.40	17,596.07	4,984.20
1985	28	134.166	1,123,536.40	18,039.68	5,149.44
1986	29	135.628	1,148,944.40	18,483.29	5,314.68
1987	30	137.090	1,174,352.40	18,926.90	5,479.92
1988	31	138.552	1,199,760.40	19,370.51	5,645.16
1989	32	140.014	1,225,168.40	19,814.12	5,810.40
1990	33	141.476	1,250,576.40	20,257.73	5,975.64
1991	34	142.938	1,275,984.40	20,701.34	6,140.88

*PE_i is in index form, with 1958 = 100

**in millions of dollars

TABLE 7-8: PROJECTIONS ON THE DEMAND EQUATION

$$TRE = -225.77(PE_i) + .083(GNP) - .26(FGSE) + 6.18(EEX)$$

(millions)

Year	TRE	QUANT.*
1975	63,249.69	529.08
1976	65,934.34	544.88
1977	68,619.00	560.29
1978	71,303.64	575.34
1979	73,988.28	590.05
1980	76,672.93	604.41
1981	79,357.58	618.44
1982	82,042.23	632.16
1983	84,726.88	645.58
1984	87,411.53	658.70
1985	90,096.18	671.53
1986	92,780.83	684.08
1987	95,465.48	696.37
1988	98,150.13	708.40
1989	100,834.78	720.18
1990	103,519.43	731.71
1991	106,204.08	743.01

*QUANT = TRE / PE_i

TABLE 7-9: PROJECTIONS ON THE SUPPLY EQUATION

(millions)

$$SE = 42.004(PE_i) + 1.83(COM) + 542.01(TREND)$$

Year	PE_i**	CON**	TREND	SE	QUANT.*
1975	119.546	27,329.85	15	63,177.19	528.48
1976	121.008	28,485.94	16	65,897.05	544.57
1977	122.470	29,642.03	17	68,616.91	560.28
1978	123.932	30,798.12	18	71,336.78	575.61
1979	125.394	31,954.21	19	74,056.64	590.59
1980	126.856	33,110.30	20	76,776.50	605.23
1981	128.319	34,266.39	21	79,496.36	619.53
1982	129.780	35,422.48	22	82,216.22	633.50
1983	131.242	36,578.57	23	84,936.08	647.17
1984	132.704	37,734.66	24	87,655.94	660.54
1985	134.166	38,890.75	25	90,375.80	673.61
1986	135.628	40,046.84	26	93,095.66	686.40
1987	137.090	41,202.93	27	95,815.52	698.92
1988	138.552	42,359.02	28	98,535.38	711.18
1989	140.014	43,515.11	29	101,255.24	723.18
1990	141.476	44,671.20	30	103,975.10	734.93
1991	142.938	45,827.29	31	106,694.96	746.44

*QUANT. = SE / PE_i

**PE_i is in index form, with 1958 = 100

***COM = 9988.50 + 1156.09(TREND)

NOTE: COM and SE are in millions of dollars.

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cost of materials (COM) is given at the foot of the Table. The value of industry shipments in electronics by 1991 is projected to exceed 106 billion dollars.

Note that the dollar values for demand (TRE) and supply (SE) are very close, but not equal. With simultaneous estimation techniques used to forecast, they would have been equal. These figures are within 1% of equality, however, Although the simultaneous estimations have been run, forecasts with these estimates were not made at the time NASA requested our efforts devoted to the turbine blade study.

The projections for the independent variables used in the demand and supply equations assume a simple linear trend. For various product lines different assumptions as to the long term trend could be used to account for changing factors such as competitive technology and changes in government spending directions. In this instance, it is highly likely, for example, that FGSE will not grow in linear fashion as projected. An examination of the projection in Figure 7-6 shows that while the regression projects a moderately high increase, the latter years show a leveling effect. Thus it would probably be better when forecasting with the individual product lines (as well as reforecasting for the electronics industry) to revise downward the FGSE value shown.

Figure 7-3 through 7-9 are graphic interpretations of the data presented in the tables. Figure 7-3 shows the actual movements of the price index for the electronics industry with the dots being actual points. The dotted line represents the regression fit and solid line the forecasts based on the regression analysis. All of the figures are set up in the same manner. They are as follows:

Figure 7-3 - Price Index for Electronics
Figure 7-4 - Electronics Exports
Figure 7-5 - Real Gross National Product
Figure 7-6 - Federal Government Expenditure on Electronics
Figure 7-7 - Cost of Materials in Electronics
Figure 7-8 - Demand
Figure 7-9 - Supply

Two viable approaches could now be taken regarding the incorporation of crystals into the study.

(a) The share of crystals in the electronics industry totals could be estimated and the future market of crystals determined in that manner.

(b) The share of crystals in various product lines could be estimated after the model has been tested and projected for the product lines. Crystal market demand could then be projected by summing the individual product demands for crystal.

Of the two approaches, the second would appear more promising for two reasons: (a) it would allow a more accurate appraisal across product lines and (b) it would also save disaggregation of crystal types by each product line. This latter step is essential to eventual evaluation of the feasibility of space processed crystals. Data collected toward this end are shown in Table 7-10.

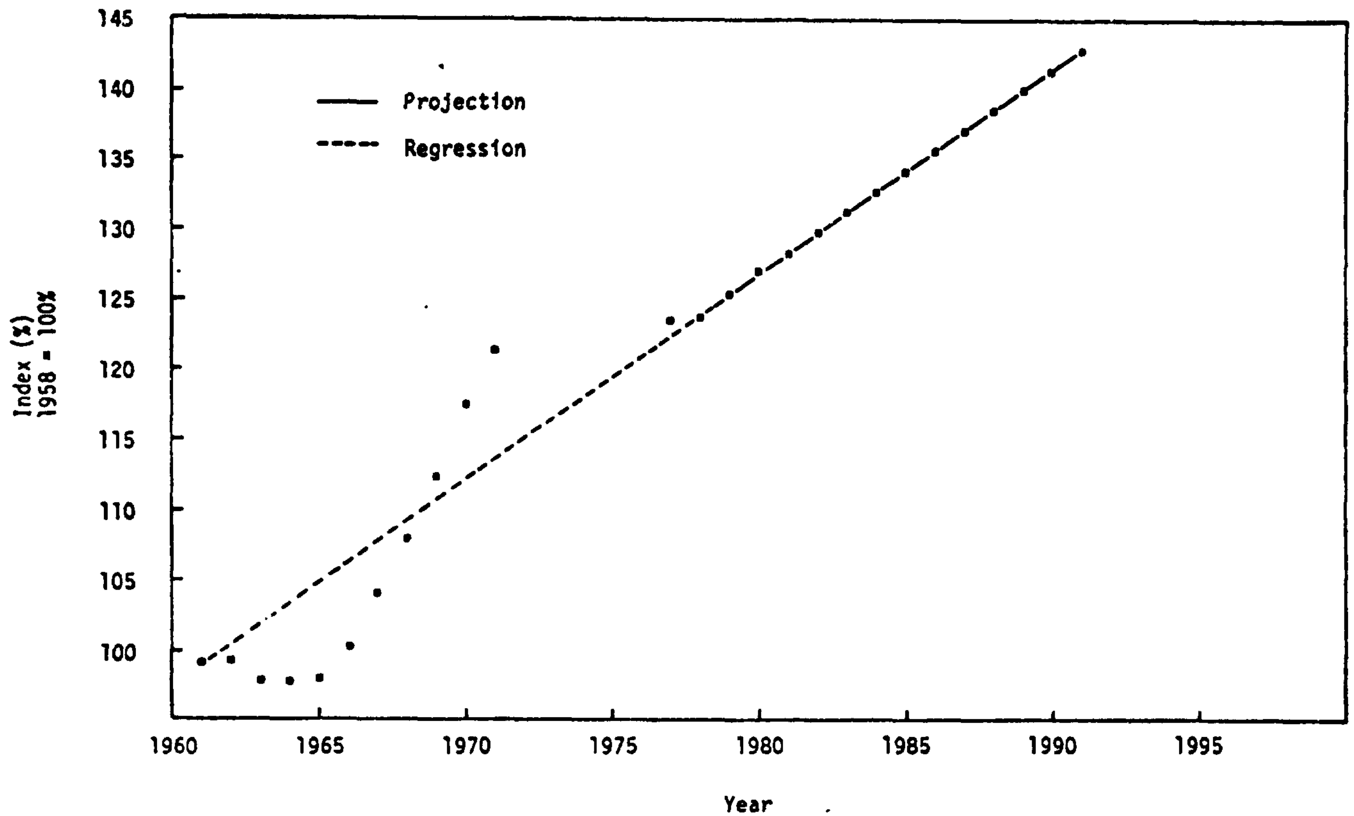

FIGURE 7-3: PRICE INDEX - ELECTRONICS

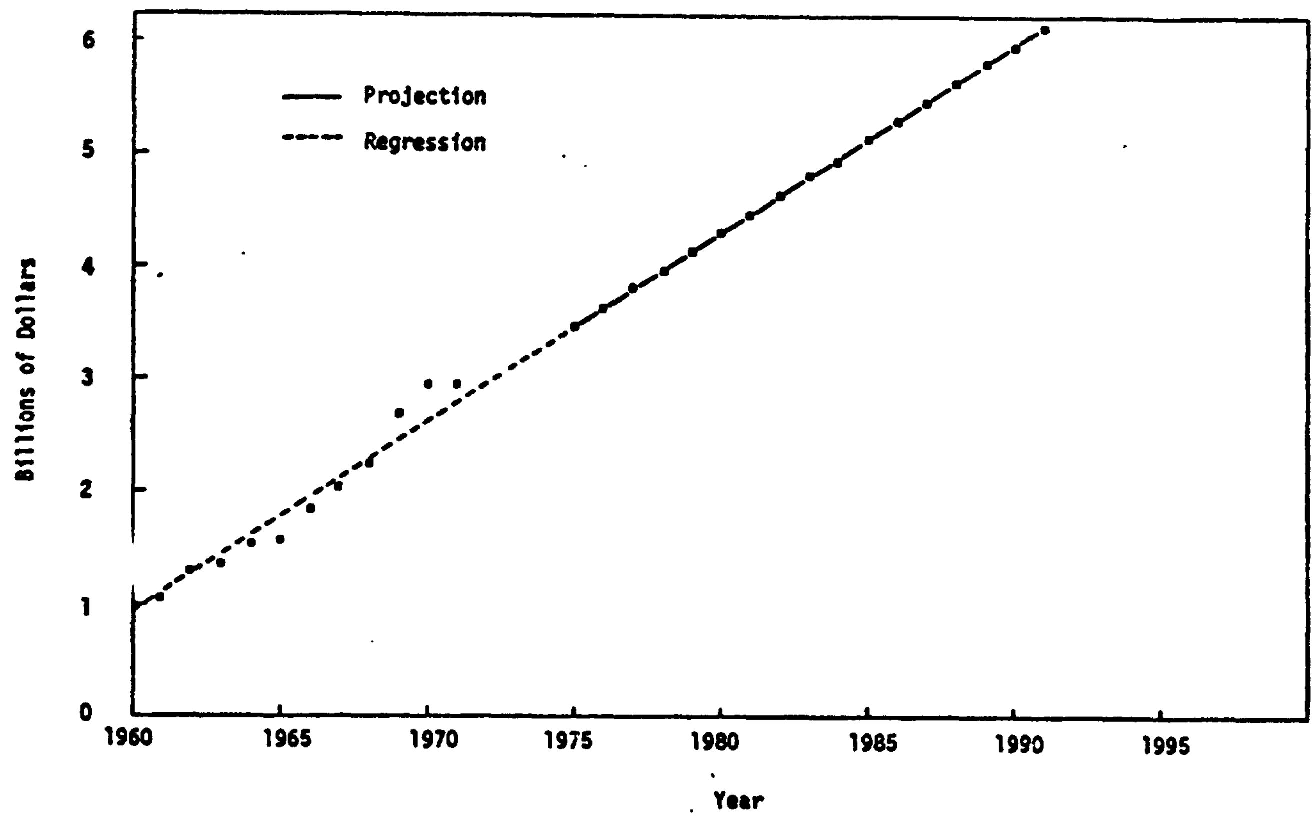

FIGURE 7-4: ELECTRONICS EXPORTS

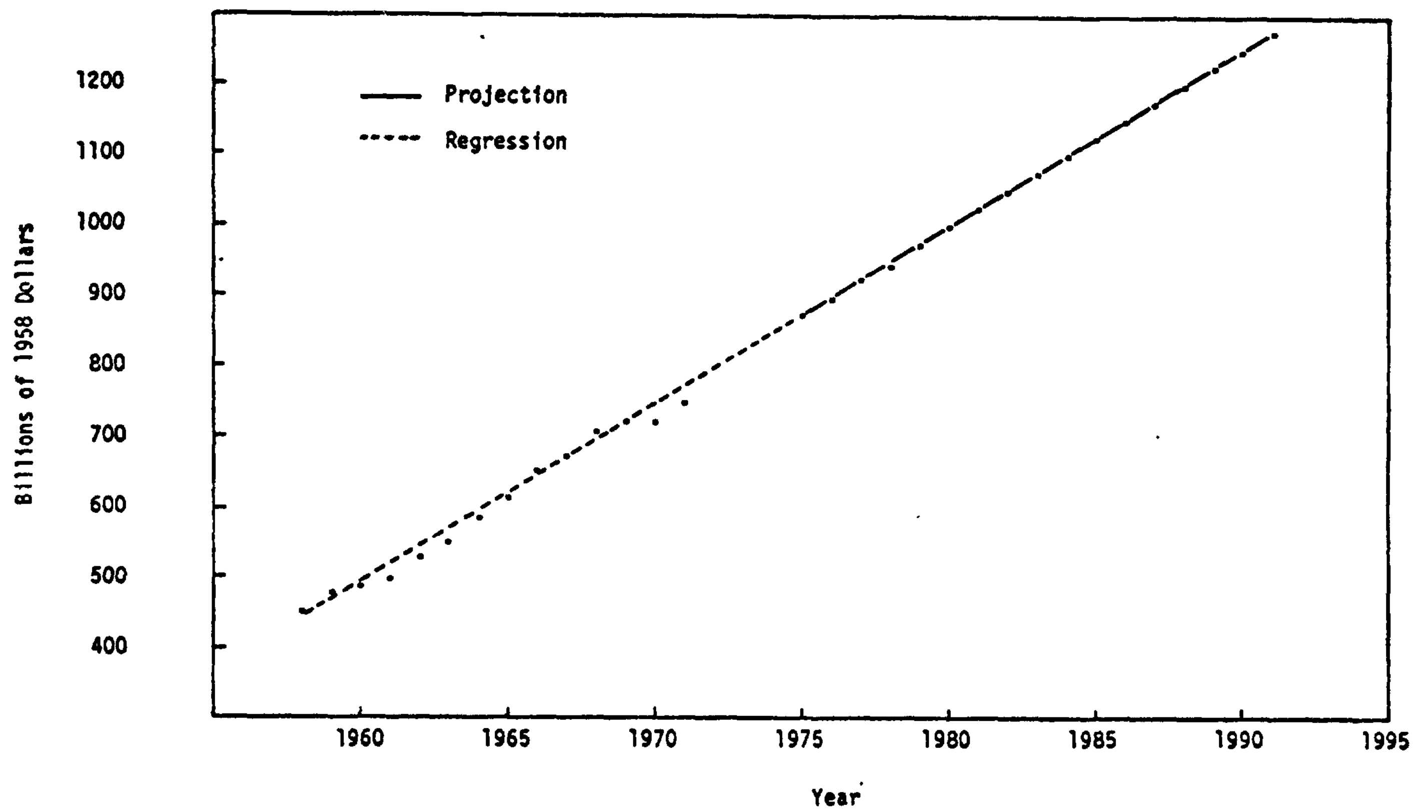

FIGURE 7-5: REAL GROSS NATIONAL PRODUCT

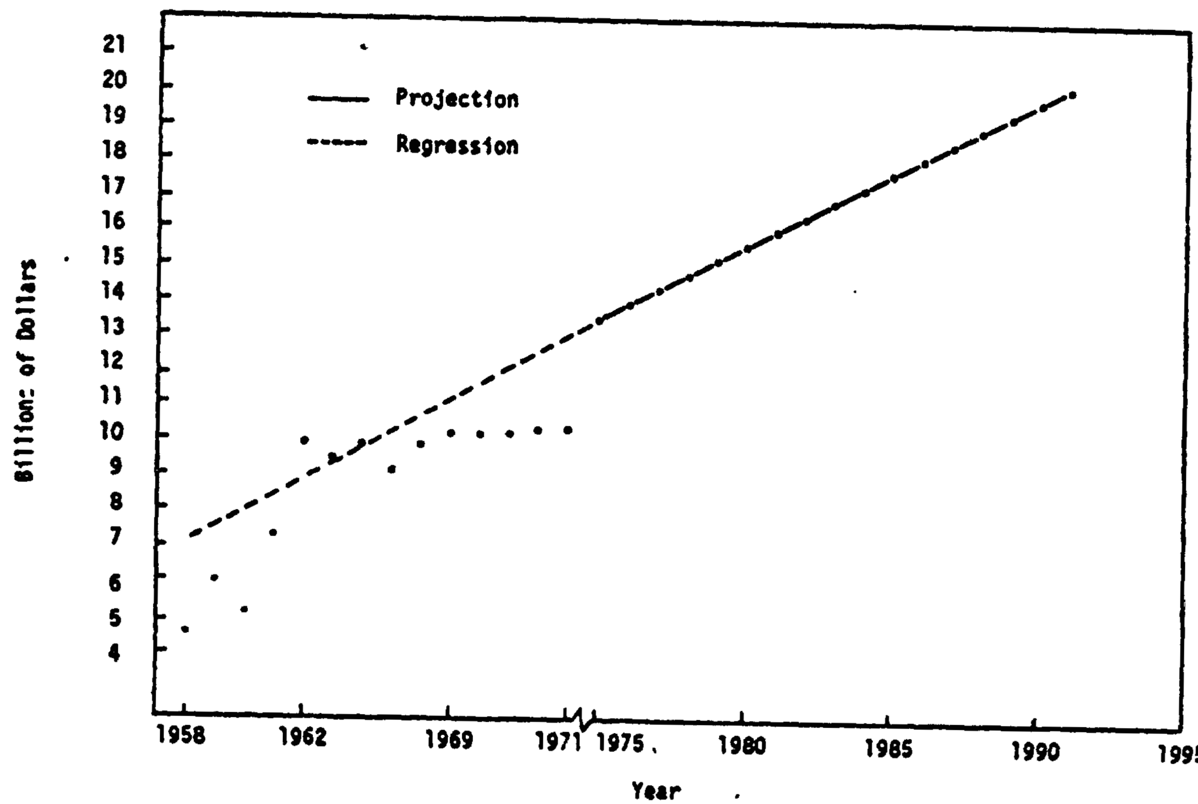

FIGURE 7-6: FEDERAL GOVERNMENT SPENDING ON ELECTRONICS

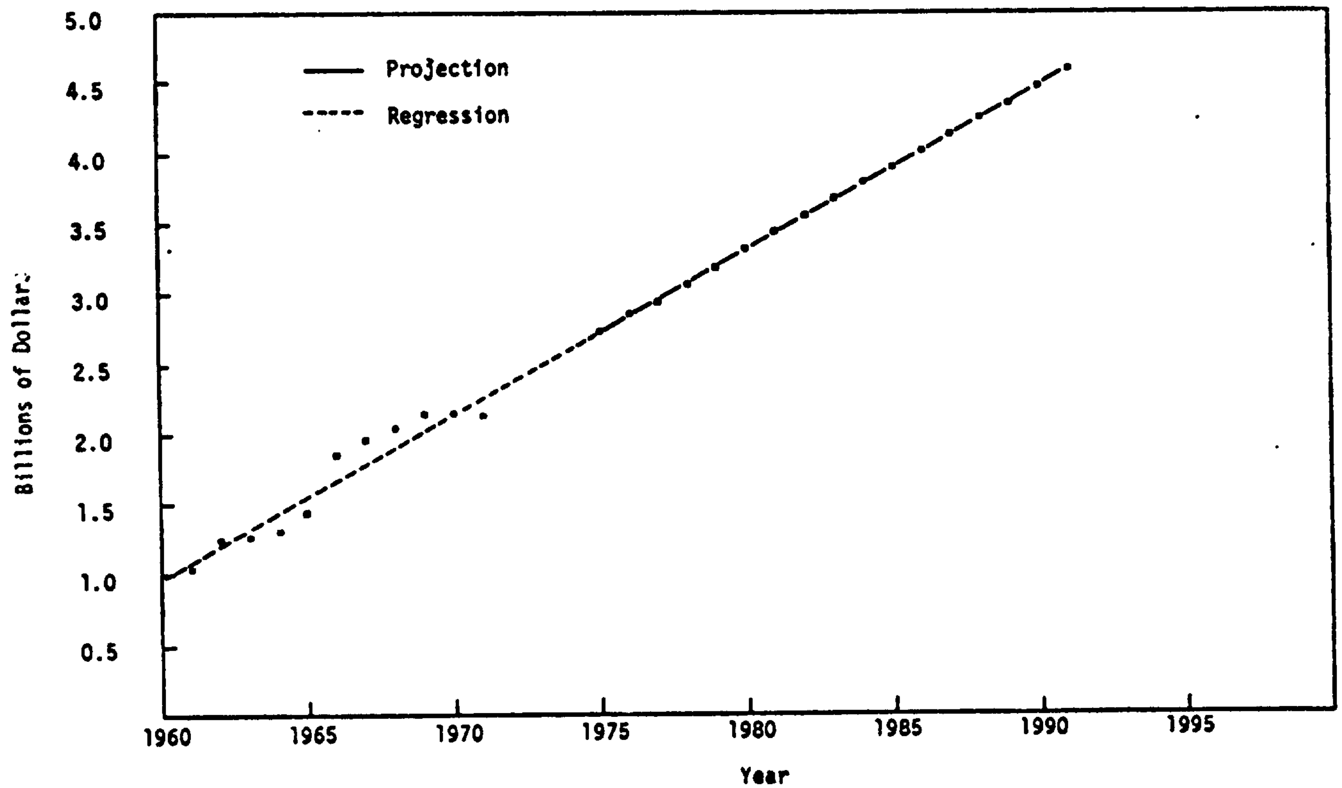

FIGURE 7-7: COST OF MATERIALS (ELECTRONICS)

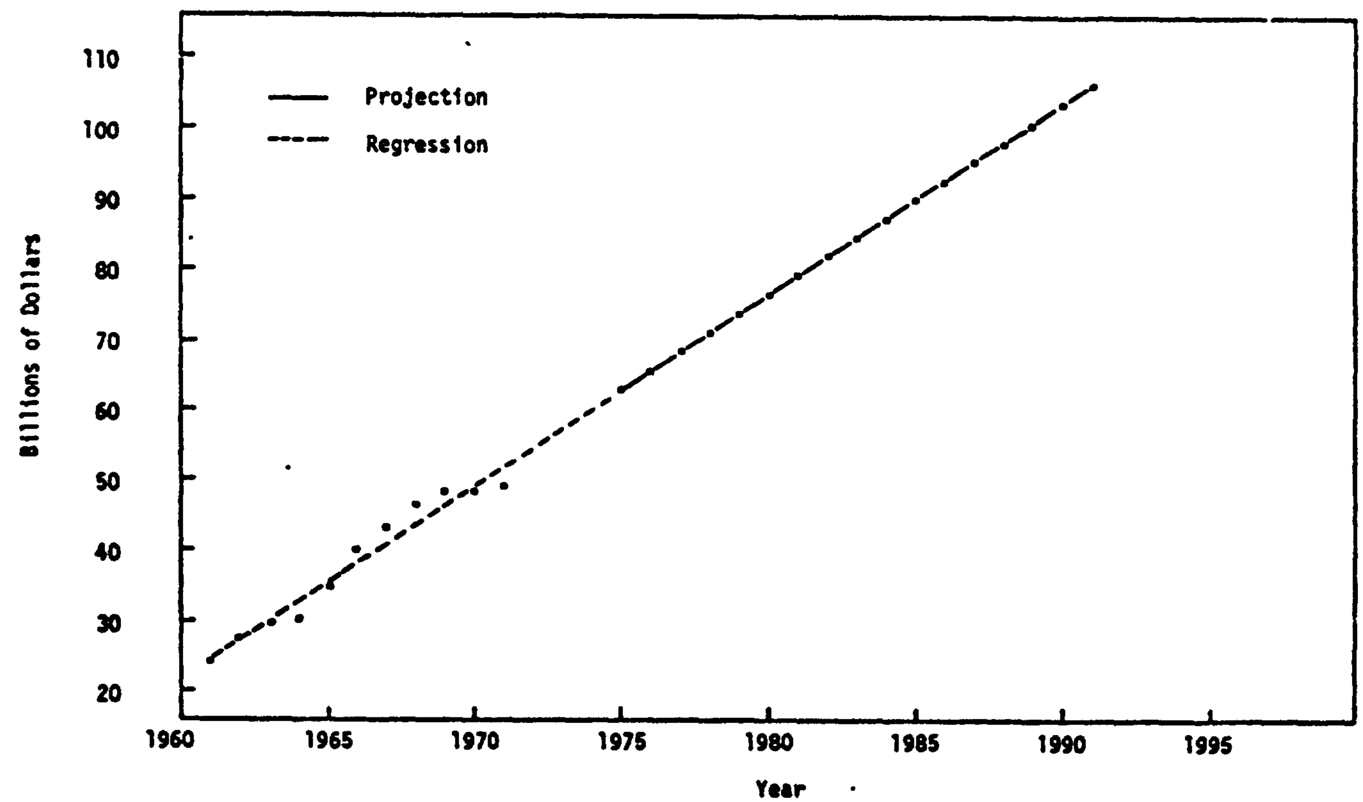

FIGURE 7-8: DEMAND FOR ELECTRONICS

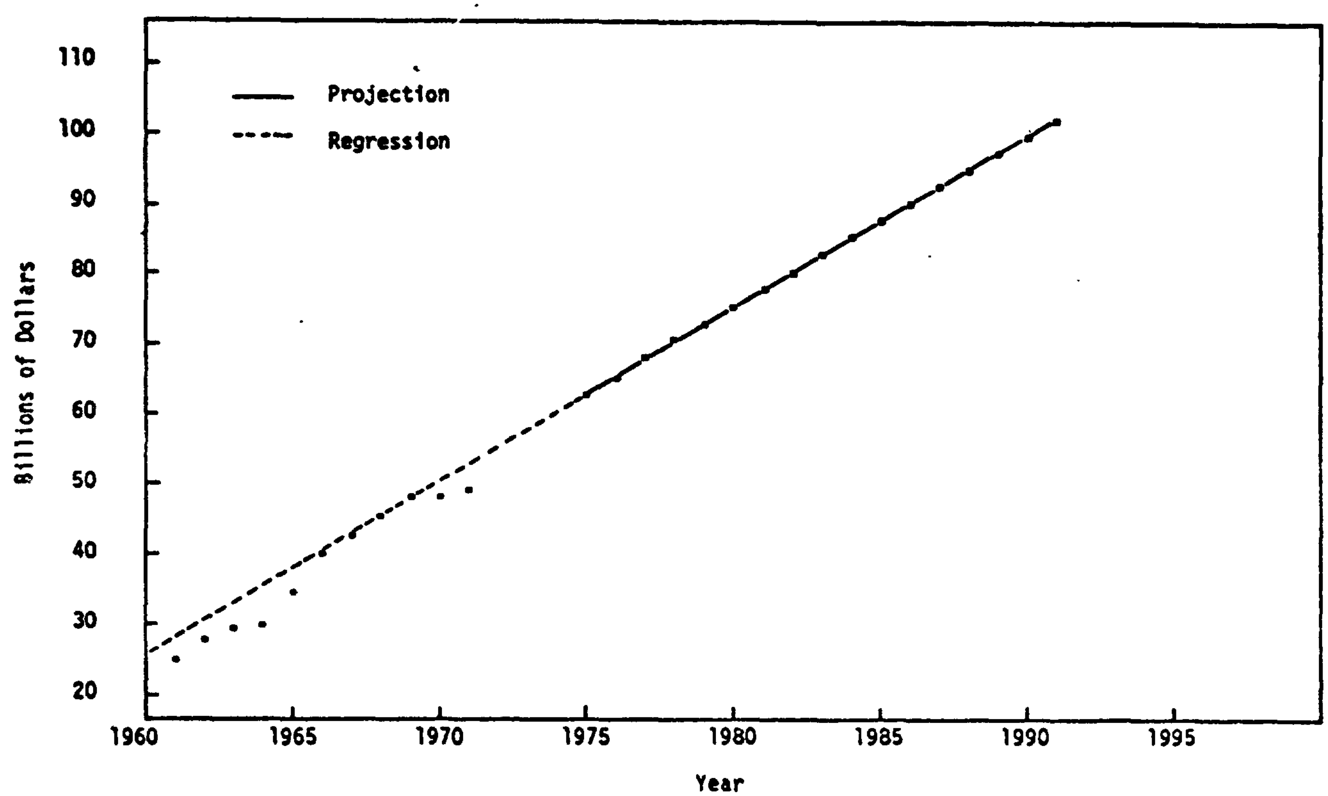

FIGURE 7-9: SUPPLY

TABLE 7-10: SALES VALUE DATA ON CRYSTAL USING PRODUCTS (MILLIONS OF DOLLARS)[8]

Year	Quartz Crystals	Communication Equipment	Medical Equipment	Crystal Can Relays	Semiconductors	Industrial Controls Equipment
1960					500.0	
1961	26.0	733.0	63.0	12.0	606.0	171.0
1962	29.0	950.0	125.0	18.0	580.0	190.0
1963	27.0	1023.0	198.0	14.0	571.0	320.0
1964	43.0	1121.0	209.0	20.0	630.0	334.0
1965	46.3	1213.9	216.5	19.5	669.6	768.9
1966	50.0	1382.5	230.6	22.2	882.3	934.8
1967	57.5	1288.8	260.5	28.2	999.0	905.1
1968	54.4	1625.2	366.3	34.2	1376.1	1021.4
1969	55.1	1788.6	347.2	33.7	1282.9	1139.4
1970	45.3	1723.4	529.9	26.1	1250.1	651.0
1971	46.0	1598.3	545.0	27.0	1251.7	660.5
1972	42.6	1743.7	524.6	24.5	1524.1	889.5
1973	48.6	2068.2	507.3	26.0	2017.7	1079.5

Year	Components	Hybrids	Crystal Filters	Pollution Monitoring Equipment
1970	4567.0	90.6	26.7	10.4
1971	4767.7	92.5	25.0	12.0
1972	4172.4	105.8	22.7	14.0
1973	4705.4	125.0	29.0	17.0

TABLE 7-10: CONTINUED

Year	Solid State Relays	Microwave Instruments	Non-Microwave Instruments
1964	1.5	55.0	399.0
1965	2.3	62.6	427.4
1966	3.2	64.8	513.2
1967	15.8	81.9	566.6
1968	17.3	84.6	599.8
1969	19.6	83.0	690.0
1970	15.5	87.1	635.4
1971	16.7	94.5	575.2
1972	9.0	108.5	725.2
1973	13.0	118.7	806.1

Year	Lasers	Optoelectronics	Integrated Circuits	LED's and LED Displays	Discrete Convex
1967	5.0	19.0	237.0	.3	561.9
1968	6.1	23.0	342.3	.8	596.5
1969	8.9	51.9	397.7	1.9	544.3
1970	8.0	36.3	432.2	4.1	572.8
1971	12.0	42.0	508.9	12.4	493.3
1972	13.7	39.8	699.6	24.0	557.9
1973	17.1	59.8	1080.6	53.0	616.0

7.7 Results of the Crystal Survey

The cover letter and questionnaire used in the crystal survey is given in exhibits 7-1, 7-2, and 7-3. The results of the questionnaire were very poor. Although trying to be realistic about response, we had anticipated a somewhat better rate of reply than obtained. None of the eleven firms that were sent questionnaires were fully responsive. Only three replied at all and only one in any detail. None of the firms were willing to disclose information on price or quantities produced. A lack of such information in government publications, coupled with non-disclosure policies make empirical work almost impossible.

A few comments were made that might prove interesting, however. These are presented for general information purposes. As promised to the firms, their identities will not be revealed.

a) Regarding response to the questionnaire and the need for space processed crystals:

1) ". . . we cannot identify any need for other than gravity-bound crystal manufacture.

For this reason, we are not responding to your questionnaire, as it is irrelevant to our requirements.

2) ". . . certain items such as value of production or production volume are considered proprietory information and as such are not furnished . . ."

3) "It has not been demonstrated that a need exists for these "superior" crystals."

4) "Presently and in the near future, I see no need. Some applications requiring reduced striations may develop.

b) On cooperation with NASA on such a venture, one firm said no, the other responding said that if their particular capabilities were needed and they felt they could contribute, they would consider the request very seriously.

c) No price or quantity information was provided except that one firm which produced only quartz crystals cited a figure of $66 per kg.

AUBURN UNIVERSITY

AUBURN ALABAMA

36830

SCHOOL OF BUSINESS

Department of
Economics & Geography

Telephone 826-4910
Area Code 205

June 26, 1974

Dear Sir:

The econometrics group at Auburn University is examining the economic feasibility of space manufacturing of crystals. The most obvious benefit to be expected from such a venture is crystals of a high degree of perfection, purity and of sizes and shapes unattainable on earth. The extremely high cost of space transportation mitigates against space production of low cost crystals. Thus only the more exotic, high cost crystals are viewed as potentials for space manufacturing. NASA, however, does not plan to take over the exotic crystal market from private enterprise. On the contrary, plans currently call for a joint commercial venture with NASA serving as a contractor for transportation. The crystals will be grown in space and processed by private firms on earth. Research efforts are presently only entering an R & D phase on this project.

Although we already have some cost information on crystals, we would appreciate your assistance in the following aspects of our study.

1. We would appreciate a current price list of crystals you produce. This will allow us to make some comparisons of earth growth to space growth costs. Any cost of production information you can supply would also be very helpful. If you produce crystals only for internal production, what valuation do you place on them? All information provided will be kept in strict confidence. Any figures used in the study will not be associated with yourcompany.

2. Would you please check the enclosed list of crystals that are used by your company or that possibly will be used?

7.8 Exhibit 7-1

3. Could you complete the enclosed questionnaire? Please return it to:

A. Wayne Lacy
Economics Dept.
Auburn University
Auburn, Alabama 36860

Your co-operation will be greated appreciated and will be kept in strict confidence.

Sincerely,

A. Wayne Lacy
Asst. Prof. of Economics

Encl. 2
AWL/jo

7.9 Exhibit 7-2 - Crystals of Interest

Aluminum Gallium Arsenide
Aluminum Nitrate
Barium Sodium Niobate
Bismuth Germanate
Bismuth Tantalate
Bismuth Titanate
Gadolinium Iron Garnet Films
Gadolinium Molybdate
Gallium Arsenide
Gallium Nitride
Gallium Phosphide
Indium Aluminum Phosphide
Indium Gallium Phosphide
Lead Germanate
Lead Tin Telluride
Lithium Germanate
Lithium Iodate
Lithium Niobate
Lithium Tantalate
Potassium Iodate
Potassium Lithium Niobate
Rare Earth Gallium Garnet Substrate
Rare Earth Iron Garnets or Rare Earth Gallium Iron Garnet Films
Ruby (Nd^{3+})
Sapphire
Sodium Iodate
Spinel
Triglycine Sulfate
Yttrium Aluminum Garnet
Yttrium Iron Garnet

7.10 Exhibit 7-3 - Questionnaire

1. Do you believe that the growth of exotic crystals can be a successful commercial venture, i.e., can a price be set that will recover all costs including transportation and a fair return?

   Yes __________ No __________ Not Sure __________

2. Do you think your firm would be willing to participate with NASA on such a venture?

   Yes __________ No __________ Perhaps __________

3. What qualifications would you place on such a venture?

4. What direction do you foresee exotic crystal prices taking in the next 6 years?

   Sharp Increase ________ Moderate Increase ________
   About the Same ________ Moderate Drop ____________
   Sharp Drop ____________

5. If you foresee a drop in exotic crystal prices, what % decrease would you expect from 1974 to 1980?

   0--10% ________ 10%-25% ________ 50-75% ________
   25%-33% ________ 33%-50% ________
   75%-90% ________ over 90% ________

6. If you foresee a rise in exotic crystal prices, what % rise would you expect from 1974 to 1980?

   0--10% ________ 10%-25% ________ 25%-33% ________ 33%-50% ________
   50%-75% ________ 75%-90% ________ over 90% ________

7. What is the type and price of the highest volume crystal you produce?

   Type ______________________________
   Price per lb. or gm. ______________________________
   Volume ______________________________

8. What is the type and price of the highest price crystal you produce?

Type ______________________________

Price ______________________________

Volume ______________________________

9. As noted, in the cover letter, it is expected that space processing will allow the growth of crystals of greater purity, greater size, and of special shapes that cannot be produced on earth. Of the crystals listed in above, which would you suggest as having the greatest application from these characteristic improvements?

Which would you suggest as having the least application?

What crystal structure not listed would you suggest as needing a gravity free growth environment that would make them more usable? What uses do you foresee for them?

7.11 References

1. Ulrich, D. E., Chung, A. M., Yan, C. S., and McCreight, L. R., "Economic Analysis of Crystal Growth in Space," Prepared for the National Aeronautics and Space Administration, Marshall Space Flight Center. Prepared by General Electric Company, Space Division, Space Sciences Laboratory.

2. Current Industrial Reports, Standard Industrial Classification Code (SIC) 36 - Electrical Equipment and Supplies, U.S. Department of Commerce.

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4. Annual Survey of Manufactures, Department of Commerce, Social and Economic Statistics Administration, Bureau of the Census, U.S. Government Printing Office, Washington, D.C.

5. Survey of Current Business, Department of Commerce, Bureau of Economic Analysis, U.S. Government Printing Office, Washington, D.C., July Editions, 1959-1973.

6. Electronics, McGraw-Hill, January Editions, 1958-1974.

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8. SUMMARY AND RECOMMENDATIONS

Reduced gravitational effects and the associated phenomena in outer space point to the possibility of the manufacture in space of improved materials, new materials, and innovative process techniques. Thus, an economic analysis using econometric and cost benefit analysis techniques was performed to determine the feasibility of space processing of certain products. The overall objectives of the analysis were (a) to determine specific products or processes uniquely connected with space manufacturing, (b) to select a specific product or process from each of the areas of semiconductors, metals, and biochemicals, and (c) to determine the overall price/cost structure of each product or process considered.

The economic elements of the analysis involved (a) developing a generalized decision making format for analyzing space manufacturing, (b) a comparative cost study of the selected processes in space vs. earth manufacturing, and (c) a supply and demand study of the economic relationships of one of the manufacturing processes. Three space processing concepts were explored to some degree for this analysis. The first involved the use of the shuttle as the factory with all operations performed during individual flights. The second concept involved a permanent unmanned space factory which would be launched separately. The shuttle in this case would be used only for maintenance and refurbishment. Finally, some consideration was given to a permanent manned space factory.

Product lines were selected on the basis of those that potentially would provide substantial technical improvement over earth processing or those which have not been producible in earth gravity. Thus, the products chosen for analysis of space processing feasibility were single crystals for electronic applications, high-purity tungsten targets for medical x-ray tubes, turbine blades for jet aircraft engines, and electrophoresis for biological applications. However, the emphasis was directed to the analysis of turbine blades midway during the project by the direction of the sponsor.

A detailed analysis of the cost of operating the space shuttle transportation system was necessary before each manufacturing process could be examined. All products or processes were analyzed as to the costs which will be incurred during space manufacture, the projected demands of such products during the 12 year planning period (1980-1991), and the benefits which can be derived from these improved products. Throughout the analysis, the assumption was made that all costs, including transportation costs must be recovered for the products to be viable.

8.1 Shuttle Costs

The cost of operating the shuttle for space materials processing should include three cost estimates: transportation costs, specific processing costs associated with the facility, and integration of shuttle payloads on the ground. However, this report is concerned only with space transportation costs. The basic assumptions used to develop transportation costs estimates were: (a) the volume of traffic anticipated by the October 1973 Shuttle Traffic Model, (b) the flights evenly distributed over the planning period with flight activity per year chosen as 12, 20, 30, 40, 56, 60, 70, and 82, (c) the cargo payload of 32,000 pounds (14.5 K), (d) the orbiter will use a 200 nautical mile orbit with an inclination of 28.5^{o} with all launches occurring at the Florida launch site, and (e) the cost calculations were based on 986 shuttle flights.

The conventions and procedures used in the analysis were: (a) the use of 1972 dollars, (b) transportation costs discounted at rates of 0, 5, 10, and 15 percent, and (c) joint costs allocated to user on basis of charge per pound of orbiter cargo capacity. Transportation charges are presented as minimum cost analysis, minimum total operating and capital amortization costs, and full costs of amortizing operating, investment, and development expenditures. Calculation of transportation costs of space processing activities at a zero discount rate utilized $326 per pound (453 gm) assuming a total of 445 flights over 12 years or 37 per year. This cost would be reduced to $260 per pound (453 gm) for 82 per year for 12 years.

Established costs involved estimating expenditures for particular elements of the shuttle system using parametric estimating techniques. These estimates do not reflect detailed engineering estimates required for actual budget requests. Adjustments were made in the cost estimates to account for productivity improvements that occur over time. These improvements involve efficiency and not technological advances. Learning curves of different degrees were used in adjusting cost data for increases in efficiency. Base line flights used 85 and 95 percent learning curves.

Operational cost associated with the shuttle involve fixed costs reflecting non-recurring development and investment expenditures, and the fixed and variable costs associated with operation. The base line operational cost per flight is estimated at $10.45 million (1971 dollars) for a total of 439 flights. This figure does not include any procurement costs of the orbiters or any development costs. It does include the elements listed on the next page.

Solid Rocket Booster	$4.28 million
External H_2/O_2	2.31 "
Program Support	1.76 "
Orbiter Spare Parts	1.40 "
Ground Operations	.27 "
Main Engine	.23 "
Fuel & Propellants	.20 "
TOTAL	$10.45 million

To determine the effect of different levels of shuttle activity on the average cost of operation, average cost curves for the 12 year planning period were calculated on the basis of different flight activities:

Total Flights	144	240	360	480	672	720	840	984
Flights per year	12	20	30	40	56	60	70	82

These flights were assumed to be distributed evenly over the 12 year period. Average annual costs for each activity level were calculated and curves fitted to these points. The average annual total costs were discounted using 0, 5, 10, and 15 percent discount rates.

The total costs per flight are dependent on a number of variables including:

a. Orbit elevation;

b. Number of launch sites;

c. Learning curve;

d. Number of flights;

e. Discount rate;

f. Flight distribution of 12 year period.

In this analysis, only the number of flights and the discount rate were allowed to vary. These are the most critical values for an economic analysis.

Total operational costs for the shuttle will vary greatly with the level of flight activity varying for $2406.5 million to $8216.4 million for 12 and 82 annual flights, respectively, at a zero discount rate. Costs per pound (453 gm) of cargo vary from $552 to $260. For an activity of 37 flights per year (445 total), the marginal costs, fixed costs per flight, and the cost per pound (453 gm) of cargo is shown below at the various discount rates.

	Discount Rate			
	0%	5%	10%	15%
Marginal cost per flight for 445 flights	$7.81 m	$5.6 m	$4.48 m	$3.67 m
Fixed costs	$1298.39 m	$999.6 m	$765.6 m	$705.5 m
Cost per pound (453 g.) of cargo for 445 flights	$326.	$253.	$203.	$170.

Non-recurring investment and development costs were contracted in the Fiscal years 1975-1980. Only the non-recurring investments costs of the orbiter and its support ground facilities were included as fixed elements of transportation costs with only $1345 million included as capital amortization.

The average cost per pound (453 gm) for recovery of non-recurring investment expenditures would be $42 for 82 flights per year. The operational costs of the orbiter at a 5 percent discount is $202 per pound of cargo. Minimum total operating and capital amortization costs of the space shuttle transportation system as related to materials space processing would be $244 per pound (453 gm) of cargo payload. If full costs of amortizing all developments costs were discounted, the maximum charge per pound or 453 gm (at 5% discount and 82 flights per year) would be $246. The maximum costs of operating and amortization of the space shuttle transportation system is thus $448 per pound (453 gm) of cargo payload. A case for a minimum total operating and capital amortization costs of $244 can be made because the development cost is incurred regardless of whether space processing is undertaken or not and since the cost involved is undertaken by the public sector. The ratio then would fall somewhere between the 5 and 10 percent discount.

8.2 Turbine Blades

8.2.1 Economic Analysis

An economic analysis was made to determine the costs and benefits of space manufacturing of turbine blades. Feasibility of space processing was analyzed by comparing the potential benefits with potential costs. Benefits were estimated by assuming a higher level of performance from a technologically superior blade (an increase of 200° temperature, doubled blade life, and 4 percent fuel reduction). Potential savings were calculated only for U.S. commercial airlines, using projections of future flight levels.

The economic analysis showed an adequate demand to justify production of space processed blades both from a quantity and benefits standpoint. Quantities demanded in 1980 and for the first 5 years are 121,987 blades per year. These quantities increase after the first 5 years for U.S. airlines and could be higher (maybe three times) with other users. Benefits of use were computed as $991.50 per blade over the 7.5 year lifetime when used as replacements in existing aircraft. These benefits increase to over $21,000 per blade over the 7.5 year lifespan when used in new aircraft, that is, new aircraft designed to fully utilize the technological advances with increased payload capacity.

Residual factory costs (maximum allowable amount that could be invested in development, launch, and direct operational cost of space factory) was computed using three separate assumptions. These assumptions are based on the transportation weight of the blade materials, the associated molds, and the storage equipment. The residual factory costs are listed below:

Weight/blade	Cost
1.5 lb. (680 gm) (best weight estimate)	$369,482,727
2 lb. (906 gm) (high weight estimate)	$113,428,182
1 lb. (453 gm) (low weight estimate)	$625,540,909

The low weight estimate may be feasible, if a manned operation using permanent molds is substituted for the automated process. If so a differential of $256,058,182 for purposes of a manned operation would be available over the best weight estimate. For the high weight estimate $512,116,364 would be freed for manned operations.

The use of space processed turbine blades could produce a total dollar savings of 4.381 billion to U.S. airlines for 100 percent adoption over a 10 year period (1980-1989). For 13 years (1980-1992), this savings could be 6.618 billion dollars. Substantial fuel savings also could be realized. These savings per year would be 111.7 million gallons (422 million liters) in 1981 increasing to 990.4 million gallons (3.75 billion liters) by 1992. For the 12 year period (1981-1992), this fuel savings would be 6.522 billion gallons (24.7 billion liters) of jet fuel.

Comparison of costs and benefits appear to make turbine blades for aircraft a viable candidate for space processing provided that the product can be manufactured to provide the assumed technological advances.

8.2.2 Space Processing of Turbine Blades

Space processing of directionally solidified turbine blades is envisioned as a simple remelt operation in which a pre-cast blade or blades are remelted in a pre-formed mold. The weight of the large number of blades (172,800) which must be produced annually, the weight of the necessary associated processing facilities, and the long process time eliminates the shuttle as a possible space factory for turbine blades. Therefore, a permanent space factory is required using the shuttle only as a means for maintenance and refurbishment.

With a shuttle cargo payload of 32,000 pounds (14.5 K) and a maximum allowable weight of blades, molds, and storage facilities as 2 pounds (906 gm) per blade at least eleven shuttle trips per year are required. For a margin of safety, monthly shuttle trips were assumed. On a monthly or 30 day basis, 14,400 blades must be manufactured giving a maximum shuttle cargo load of 28,800 pounds (13.05 K) per trip. In each 30 day period, the blades should be produced in approximately 25 days to leave sufficient time for manual maintenance and refurbishment of the permanent space factory.

Three different process systems based on (a) induction melting, (b) continuous resistance furnaces, and (c) batch resistance furnaces were evaluated. Induction melting techniques do not seem to be applicable to space processing of turbine blades. Even at fast solidification rates, too many induction units would be required for one coil per unit. In most cases, induction melting units are large and the space necessary to house all of the units plus the associated storage and handling equipment would be excessive. The number of units could be reduced by utilizing multi-coil units but, in any event, the total power required for induction melting of turbine blades is probably too great for space processing. Also, the number of blade-mold combinations (one blade per mold) which must be crew-handled during refurbishment is staggering.

Resistance type furnaces either continuous or batch hold the best possibilities for space processing. The solidification rate in either case must be high, on the order of 7 in/hr (0.05 mm/sec) to maintain a reasonable number of furnace systems. Regardless, whether a continuous or batch system is used, a multi-blade mold must be developed because, even with high solidification rates, single blade molds will require too many furnaces. In either process, the size of the furnaces required is much less than the size of the associated facilities for storage and handling. Consequently, the size of the latter is of major consideration in determining the size of the space factory required.

The total space required to house the continuous system will occupy about two times the volume as the batch process (300 m^3 to 153 m^3). Also, the materials handling equipment for the continuous process likely will be more complex than for the batch process. Power requirements for each process (24 kw for continuous and 80 kw for batch) border on being reasonable but new methods of obtaining electrical power should be investigated. The use of removeable mold storage compartments would decrease the number of blade-mold units which need be handled during refurbishment. In considering all aspects, a multi-chamber batch resistance furnace process using a multi-blade mold (6 blades per mold) seems to offer the best possibility for turbine blade processing in space.

The molds used in space processing of turbine blades are very important. In both cases of continuous and batch resistance systems, an allowable mold density was calculated. The use of reusable pre-cast molds in which a pre-cast blade is inserted on earth necessitates the use of a storage system during shuttle transportation to the space factor. The allowable mold density, thus, was determined on the bases of the maximum weight limitations of 1.0, 1.5, and 2 pounds (453, 680, and 906 grams) per blade for the blades, molds, and storage system. The storage system was designed using either a boron-aluminum composite or the low density alloy LA141A (Mg-14Li-1Al). There was very little difference in mold densities using either material for the storage system. The limitation of one pound (453 gm) imposes restrictions on the density (average of 2.4 gm/cm^3) of the mold and would reduce the number of possible mold material candidates. Increasing the allowable weight to 1.5 pounds (680 gm) per blade increases the allowable mold density to over 5 gm/cm^3. Mold density would no longer be a major factor in the selection of the mold material. Naturally, this assumes a thin-shelled mold (0.3 cm thick) for maximum heat transfer through the mold wall.

New technological advances must be made in order to minimize the number of furnaces reuqired and, thus, decrease to a reasonable amount the associated materials storage and handling equipment. These advances must be mainly in the areas of mold materials and design, furnace design, and the determination of the fastest possible solidification rate to obtain the desired alloy properties. All aspects of design for all the different associated equipment necessary for production are dependent on solidification rate (rate of production) and the number of blades which can be processed per mold. These determine the number and size of the furnaces, size of the materials storage facility, the space requirements to house the entire system and the total power requirements.

All of the processes outlined depend on obtaining high solidification rates and blade-mold compatibility. The dimensional tolerances of the blade depend on the compatibility between the mold and the blade prior to and during the entire process. Technologically, this may be the greatest handicap to overcome. At the present time, it is felt that the technology required for construction of the basic furnaces, the materials storage facilities, and the materials handling equipment is available. However, two questions remain.

a. Are the high solidification rates required to reduce the number of furnace systems capable of obtaining the necessary alloy properties?

b. Can a mold material be found that will be satisfactorily compatible with the process?

8.3 High-Purity Tungsten X-Ray Targets

High-purity tungsten for medical x-ray tubes was selected for consideration because improvement in the quality of x-ray pictures would produce external benefits to individuals, target life could be lengthened, and tungsten targets have a high value per pound (453 gm). Space manufacturing by containerless levitation melting would be expected to increase the purity of tungsten. An improved tungsten target would have higher milliampere ratings and smaller focal spots which would result in greater x-ray detail. An improvement of these characteristics result in higher thermal stresses on the target and require tungsten of higher purity.

The economic potential of high-purity tungsten targets was assessed by: (a) estimating the existing number of x-ray machines and tungsten target components, (b) estimating the future demand for replacement targets, and (c) estimating the demand for new x-ray machines and component x-ray tubes. Total demand for x-ray tubes for new machines and replacement purposes is estimated as 32,343 units in 1980 and 39,974 units in 1991. At the current price (approximately $200 per tube) this means an expenditure of about $120 million (1984 dollars) by 1991. At present, it is assumed that a 1.5 pound (680 gm) x-ray target would cost $130. The total target compo: ent cost of x-ray tubes in 1991 would be about $718 million dollars.

The success of space processing of tungsten targets does not appear to be dependent primarily on cost cutting by reducing the rhenium in the tungsten. To be successful, there must be an extension of target and tube life beyond the average two year intensive use life which now exists. A considerable increase in tube life would be required as the transportation costs associated with shuttle operations exceed the existing earth production cost. An estimated operating cost of $162 per pound (453 gm) and a capital amortization cost of $95 per pound (453 gm) is found for a 10 percent discount rate and 984 flights. When all costs, operating and amortization, are covered, the space transportation costs (not including processing costs) would be about $257 per pound, while at present, the manufacture cost is $87 per pound (453 gm). Thus, a three-fold increase in target life is required to cover space transportation costs.

On the other hand, if the only cause of x-ray tube repla nt was failure of the target, a doubling of tube life would amount to a cost saving of little under $2,000 (manufacturer's price) per unit. In this case, tungsten targets would constitute a reasonable candidate for space processing. Assuming an average life of the tube as 5 years, and a 15 percent discount rate, a doubling of tube life would result in cost savings of $220,474,000 for manufacturer's sales and $14,953,000 for manufacturer's value.

All benefits are based on continued growth in demanu for radiological health services at the rate experienced in t^ recent past. These rates may not be continued. The level of benefits which will be achieved is not as certain as the level of costs that will be incurred. Cost of the processing facility was not determined because this cost would have to be excluded from the benefits of the space process.

8.4 Electrophoresis of Biological Material

Gravity limits the extent to which certain biological products can be produced especially in the area of purification. Near zero gravity conditions may enhance the purification of the products. In this report, the biological manufacturing processes were restricted to electrophoresis methods such as: (a) continuous deflection, (b) isoelectric focusing, and (c) isotachophoresis.

Seven biological candidates were evaluated. These seven candidates were:

a. Pure samples of four subclasses of IgG;

b. Pure cultures of Beta cells;

c. Pure cultures of tumor cells;

d. Urokinase producing cell;

e. Pure samples of antihemophilic factors;

f. Pure cultures of B & T cells;

g. Pure cultures of stem cells without compliment fixing cells.

The most promising candidate is the separation of immunoglobulin (IgG) into its four subclasses by means of isoelectric focusing electrophoresis. Only 100 grams of IgG separated into its subcomponents could provide the U.S. needs for a year. This amount could provide serum that would be reproduced in animals. Only one flight per year would be required to provide this amount. This could be done in a regular shuttle flight. Benefits of space processing of commercial IgG depend on the extent of improvement of diagnostic tests for agammaglobulinemia resulting from the use of space processed serum and the number of tests performed.

In 1973, it was estimated that a test was performed on one out of every 219 persons in the U.S. This relationship is not expected to change during the 12 year planning period. Thus, the number of tests to be performed was estimated to increase from 1,023,434 in 1980 to 1,135,365 in 1991. In 1973 dollars, this represents hospital costs of $12,281,000 and $13,624,000 for the beginning and terminal years of the planning period, respectively. The total cost (not discounted) for the projected tests (17,940,848) would be about $215,290,000. The total cost resulting from the addition of an orbiter shuttle flight required to perform the zero gravity electrophoresis processing represents about 39 percent of the hospital cost of a complete IgG test. Increased diagnostic efficiency may warrant the estimated cost of $16.70 for the "new" test.

The calculated costs were based on the assumption that the entire cargo space of the orbiter is required to perform the electrophoresis processing. Shared flights would reduce the cost of producing serum. Benefits should be derived from more efficient diagnostic tests resulting in a reduced number of visits to the doctor's office and more rapid diagnosis of a wide range of diseases.

8.5 Crystal Study and Econometric Model

An econometric model was developed to predict demand and supply figures for crystals during the period of 1975-1990. Included in the model is an equation to predict impact on investment in the crystal-growing industry.

In fact, two models are presented:

a. A theoretical model which follows strictly the standard theoretical economic concepts involved in supply and demand analysis. There are severe data limitations which prevented comprehensive testing of this model.

b. A modified model version which was used for testing existing data sources.

Data on quantities of crystals sold in this country were not available and replies to a mailed survey to crystal manufacturers were poor. Other problems encounted were the locating of data on specific prices and costs of production in certain strategic crystal using product lines. The absence of these data forced modification of the model to enable testing procedures.

The econometric model to be testable by the electronics industry as a sample was modified mainly by the following:

a. Quantity demanded replaced by total revenue as dependent variable in demand equation;

b. The total revenue for the electronics industry variable is price times quantity for all elements included within the industry instead of simple quantity variable;

c. Instead of directly employing a price variable, a price index for the electronics industry was used;

d. Value of industry shipments used to denote or proxy demand.

Other minor modifications also were made. For testing, the input considered of historical data, projected data, and estimates of the proportion of crystal value in each product line tested. The value of electronic industry shipments by 1991 was projected to exceed 106 billion dollars. Projections for independent variables used in the demand and supply equations assumed a simple linear tread but are likely to be somewhat less.

The incorporation of the crystal study presented problems for econometric analysis because of the almost total lack of time series data. Crystal data proved to be too short term for the model in general. Two approaches could be made to incorporate crystals into the study. The best approach seems to be that of estimating the share of crystals in various product lines after the model is tested and projected for the product lines. Crystal market demand could then be projected by summing the individual product demands for crystals. However, work on the crystal study and the econometric analysis of crystals was terminated at the request of NASA project directors. A more in depth study has been funded with another contractor.

8.6 Recommendations

It was assumed in this study that nonexisting engineering technology necessary for the products and processes did in fact exist. Thus, during the economic analysis of space processed materials and, in particular, of the turbine blades several problems were identified. Therefore, the following recommendations are made:

a. An intensive investigation to determine the optimum solidification rate under zero gravity conditions for turbine blades with unidirectional properties should be undertaken. This study should include understanding the effect of the blade shape on directional solidification. This recommendation is predicated on the fact that the economical space processing of turbine blades is a function of the turbine blade solidification rate.

b. The development of a thin-walled turbine blade mold capable of holding several pre-cast blades should be undertaken. The mold which is a key to turbine blade production should be reusable, have high thermal conductivity, high shock resistance, and be capable of easy blade insertion and removal.

c. Space power plants capable of higher continuous power output (200 to 300 kw) should be developed for space processing. Solar concentrating furnaces should be designed and developed for shuttle experiments such as metal melting which have high power requirements. These experiments are necessary prior to the establishment of final manufacturing processes. Even though, nuclear power generation is not feasible for the shuttle, nuclear systems may prove effective for unmanned stations since extensive shielding is not required. Launch requirements would necessitate a light weight nuclear system.

d. Containerless levitation melting techniques and associated fabrication processes for high-purity tungsten or other materials should be developed further. At the present time, the size of individual melts is small and the production rate is low. Also, the shape produced by containerless melting must be modified for final use and this fabrication process can be a source of contamination.

e. The effects of near zero gravity or reduced gravitational conditions on electrophoretic processes should be determined since the results from electrophoretic experiments on Apollo and Skylab have left many questions unanswered or prompted more.

f. A series of space processing experiments to provide data of a scientific and engineering nature should be undertaken to provide data for an economic analysis prepared on the basis of a more complete predicate.

g. Cost data for the development, construction, launch, and maintenance of a permanent space station should be generated in order to predict the economics of future space processing.